Aviation Safety Program

Integrated Vehicle Health Management

Technical Plan Summary

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This document was developed over the past several months by NASA to define the rationale, scope and detailed content of a comprehensive Aviation Safety, Integrated Vehicle Health Management research project. It contains reference to past work and an approach to accomplish planned work with applicable milestones, metrics and deliverables. The document also references potential opportunities for cooperation with external organizations in areas that are currently considered to be of common interest or benefit to NASA. This document should be considered a reference document and not a completed research plan.

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Integrated Vehicle Health Management (IVHM) Executive Summary

Mission:

Develop technologies to determine system/component degradation and damage early enough to prevent or gracefully recover from in-flight failures in both the near-future and next-generation air transportation systems, and to provide enabling technology for space exploration.

Goals:

Reduce system and component failures as causal and contributing factors in aircraft accidents and incidents.

Provide continuous on-board situational awareness of vehicle health state for use by the flight crew, ground crew, and maintenance depot.

Objectives:

Develop tools and techniques to:

- Determine the state of subsystems such that the state of the entire vehicle can be determined for accurate prognosis,
- Diagnose coupled degradation/malfunction/failure/hazard conditions and predict their effects on vehicle safety,
- Mitigate damage/degradation/failures in-flight.

Develop a public database and testing capabilities for IVHM technologies.

Approach:

- Develop and employ virtual and real sensors to assess subsystem states,
- Couple state awareness data with physics-based and data-driven models to diagnose degradation and damage caused by environmental hazards and electro/thermo/mechanical failures,
- Integrate sub-system information to provide diagnostics and prognostics for the entire vehicle, including using data from one subsystem to provide information for another,
- Develop locally-controlled mitigation techniques to extend safe operation time.

1.0 Technical Plan

Integrated Vehicle Health Management (IVHM) systems offer the potential to improve safety, reduce costs, and improve performance in every aircraft class. However, many IVHM technology components are too immature for aircraft application and many tools for supporting their implementation in aeronautics applications do not yet exist. Over the next five years, NASA plans to close IVHM technology gaps and create a sustainable pipeline of tools and techniques for developing and deploying IVHM technology. This technical plan summary describes NASA's plan to develop databases, tools, and hardware subsystems to be leveraged by industry as they move forward in adopting IVHM technologies for the collective benefit of aeronautical systems worldwide.

1.1 Relevance

The IVHM Project goal is to improve the safety of both the near-future and next-generation air transportation systems by reducing system and component failures as causal and contributing factors in aircraft accidents and incidents. Data from the FAA and NTSB are clear: subsystem and component failures and hazards together contribute 24% to on-board fatalities, and are underlying factors in many of the 26% of the accidents caused by loss-of-control in-flight. In addition, JIMDAT problem statements clearly show that commercial airliners have many unresolved maintenance issues that lead to safety problems. Graphic examples of how improper maintenance and malfunctions/failures directly affect safety are given anecdotally by the recent crash of Helios Airways Flight 522, American Airlines Flight 587, and the explosion of SpaceX's new rocket. In each of these accidents, human failure to notice and assimilate system state data contributed directly to catastrophic crashes.

IVHM technologies have the potential to substantially improve aviation safety, hence supporting the safe implementation of the Next Generation Air Transportation System (NGATS).

1.1.1 Accident/Incident Data

The primary contributor to fatalities in the worldwide commercial fleet over the past 17 years, controlled flight into terrain, is no longer a major concern in the US because of regulations requiring the implementation of enhanced ground proximity warning systems. The second largest factor is loss-of-control in-flight; technologies covering this are being planned by the Integrated Resilient Aircraft Control project. The remaining non-operations-related causes of fatalities are all addressed by the IVHM project, including: system/component failures or malfunctions, ice, and windshear or thunderstorm. The number of fatalities caused by the sum of these factors (24% of all accidents) is similar to those caused by loss-of-control (26%), and it should be noted that these hardware and system malfunctions are a contributing factor in some loss-of-control accidents.

CAST has developed a safety strategy to reduce risks associated within these accident categories. Of the 47 identified safety enhancements, 30 have been completed, and 17 are underway. Completed safety enhancements include process improvements, such as updating procedures and training, and an improved safety culture. An analysis of risk reduction from the CAST safety enhancements predicts a 73% reduction of safety risk by 2007, and a 75% reduction by 2020. Remaining risk in 2007 for each accident category assuming the 47 elements of the CAST Safety Plan were implemented worldwide was estimated. This figure shows that safety risks still remain in the accident categories associated with system and component failures (both power plant and non-power plant), and icing.

NTSB accident data covering 7,571 US-registered transport aircraft from 1980 to 2001, broken down by the accident causes (hardware malfunctions only), shows that 52% of hardware- induced accidents were aircraft system related, 36% were caused by propulsion system components, and the remaining 10% were caused by failures in the airframe. Of these, landing gear was the single biggest contributor (causing 36 of the 91 hardware-induced accidents), turbine/turboprop engines caused 33, and flight controls caused 10 of these accidents. Similarly, incident data again shows that turbine engines and landing gear were the largest contributors to hardware-induced incidents, each causing 19%, and flight controls causing 9%.

FAA data covering 40,964 incidents involving US airplanes from 1998 through 2003 shows that for commercial air carriers, commuters and on-demand air taxis, about 67% of incidents were caused by the combined causes of system and component failure and malfunction, fire/smoke, and power loss.

1.1.2 Industry/Government Recommendations

The CAST reports have identified key safety problems and possible interventions to address the causes of aircraft accidents. In general, the failure of flight crews to correctly interpret, process, and cross-check available relevant data, to maintain aircraft system status awareness, and to understand the impact of inoperative or degraded systems on aircraft performance is noted as a critical problem. Other problems noted in the CAST reports include: 1) lack of realistic simulation of propulsion system malfunctions and aircraft response, 2) lack of adequate trend information, 3) inadequate or lack of sensors/ equipment to indicate damage from Foreign Object Damage (FOD), Bill of Material Object Damage (BMOD), or ground equipment collision, 4) improper assessment of failure modes and effects analyses, 5) failure to provide warning of flight critical system unsafe status, and 6) ice protection system design inadequate for conditions encountered. Some of the recommended interventions include: 1) ensure that design logic for warnings and equipment failures to be annunciated to the crew do not cause nuisance warning that would contribute to crew complacency, 2) provide real time assistance to flight crews with onboard system failures and diagnostics (e.g., data link transmittal to ground support), and 3) conduct research to develop sensors or other equipment to detect and annunciate impact damage by FOD, BMOD, or collisions.

Similarly, the NIA's "Aviation Plan for American Leadership" identified 29 technology elements that need to be matured. Of the 29 elements, 12 of them are related to IVHM technologies.

Finally, the Joint Planning and Development Office is developing an integrated plan for the NGATS, as presented in its December 2004 report. The report states that avionics will play a key role in transforming the US air transportation system: future aircraft will sense, control, communicate, and navigate with increasing levels of autonomy. Emerging environmental threats precluding the safe adoption of more autonomous avionics systems include electromagnetic interference (EMI) from sources such as high-power transmitters, radars and portable electronic devices carried onboard by passengers, and from atmospheric neutrons that can cause single event effects. Although the atmospheric neutron environment is relatively well known, the effect of this environment on aircraft flight systems is not, even though it has been established that atmospheric neutrons are the cause of single event upsets in avionics. In addition to new avionics systems for increased autonomy, the NGATS vision states that future air vehicles will utilize new materials, fuels, and design processes for improved resistance to impact damage and flammability. The report states that automatic health monitoring combined with self-healing systems in aircraft will improve reliability and predictability of service. The Joint Program Development Office report calls for changes in aircraft technology to enable operations in a wider spectrum of weather conditions so that capacity will not be reduced during most inclement weather conditions. Technologies required to enable operations in most inclement weather conditions include characterization and mitigation of lightning effects and icing on flight critical aircraft systems.

1.1.3 Market Trends

The airline industry is facing severe economic pressures, posting $32B in cumulative net losses between 2001 and 2004. Profitability is directly impacted by costs, which include ownership costs (purchase price, financing, depreciation, insurance) and operating costs (fuel, fees, maintenance, and labor). Of these, health management technologies directly impact maintenance costs, and can indirectly impact fuel costs and fees by providing enabling "intelligent" technologies that can be used to reduce fuel burn and fee-invoking emission.

Worldwide, airlines spend $31B per year on aircraft maintenance: 31% is for engine maintenance, 27% is for aircraft and engine heavy maintenance (i.e. schedule C and D checks), 23% is for line maintenance, 16% is for component overhaul, and 3% is for modernization and refurbishment. Labor costs for C and D checks for large commercial aircraft (including regional jets) totaled $2.1B worldwide in 1999. Typically, there are 12 maintenance labor hours per aircraft flight hour (excluding shop visits) to meet FAA airworthiness directives or for modernization. In addition, 5-10% of all flights are cancelled for un-scheduled maintenance.

Airlines are demanding increased time on wing and reduced engine shop visits in terms of A-checks. Engine and aircraft maintenance requirements are decreasing, but avionics and electronics maintenance and testing requirements are increasing. On-condition engine maintenance is becoming more prevalent than scheduled maintenance. Modular replacement or repair is popular, and is offered as an on-site service. Periodic maintenance leaves few original parts in the engine, so the frequency of unscheduled engine maintenance doesn't increase with age the way it does with aging airframes. The cost of engine overhaul depends on engine size, age and operating profile; 70% of the cost is for hot section repairs.

In 1996, 55% of aircraft heavy maintenance was done by the airlines themselves, but outsourcing is increasing. There is international competition for engine servicing in growing markets like China. In 1996 there were 330 independent equivalent maintenance bays worldwide; in the US, supply (149) exceeded demand (68). Airlines will go where the cost is lowest if the quality is acceptable, so labor saving health management technologies should primarily impact jobs overseas.

In the military fleet, data from the Oklahoma Repair Center shows that engine maintenance is the #1 factor in force readiness. The DoD spends $3.5B yearly on sustainability vs. $1.3B on acquisition. Their goal is to lower repair costs by 30%, and they see health management technologies as critical to achieving that goal. Clearly the cost savings of having more existing aircraft flying, rather than purchasing enough to compensate for sidelined vehicles, are also enormous.

1.1.4 Current State-of-the-Art

The Joint Strike Fighter (JSF) program embodies the state-of-the-art in aircraft IVHM. This program has incorporated prognostics health management (PHM) into its design, using sensors, advanced processing and reasoning, and a fully integrated system of information and supplies management. The on-board JSF PHM system is hierarchical, dividing the aircraft into areas such as propulsion and mission systems. Area data is generated by a mixture of dedicated, purpose-built sensors and analysis on existing control sensors to identify degradation and failures, compiled and correlated by area reasoners, and then correlated by system-level model-based reasoners. Maintenance data-links telemeter vehicle health data to ground-based information systems focused on maintenance and management of the supply chain. Prognostic events are detected by prognostic built-in-test, automated post-flight trending, and reasoning, with an emphasis on disambiguating sources of degradation rather than failure. Ground-based knowledge capture is used to sift through flight data. An autonomic logistics information system provides logistic support to the end user and provides off-board trending across the entire JSF fleet. The JSF PHM system is still in the design phase, and it is widely acknowledged that much work remains to build a reliable, effective health management system. Much of the integration of health management information is done manually after the flight. Commercial health management systems lag the military, but commercial suppliers have a keen interest in applying health management technologies to keep pace with changing market conditions and the need for reduced maintenance costs to ensure economic viability of the operators and equipment manufacturers.

1.2 Technical Approach

Our IVHM research is intended to address the commercial aviation needs described above, and to complement many of the advances made under recent DoD programs such as the Joint Strike Fighter program and the DARPA Prognosis program by 1) developing publicly-available databases and test capabilities, 2) providing knowledge about the fundamental physics and associated effects of damage and degradation caused by specific damage mechanisms and environmental hazards relevant to commercial aircraft, 3) developing fundamental tools for automating knowledge capture, 4) developing fundamental technologies for communications within constrained environments, 5) developing design, analysis, and optimization methods for synthesizing robust IVHM system architectures, and 6) developing fundamental V&V tools and techniques to quantify the performance of health management technologies and systems. We expect that the NASA investment in this research will accelerate the introduction of health management technologies into commercial aircraft, while also providing fundamental knowledge of benefit to the military and NASA's Space Exploration program. Our intent is to develop knowledge, databases, codes and hardware subsystems that will be publicly available for use by others in developing their own IVHM systems, addressing safety, cost, and performance.

Our concept for IVHM operations includes on-board and off-board components. The on-board function monitors, detects, diagnoses, prognoses, and mitigates damage, degradation and/or failures. In most cases, mitigation consists of notifying the flight crew or ground support, but the vision is to also include locally-activated response mechanisms such as self-healing materials. The off-board function provides fault and failure diagnostics to the ground crew, hazard information to ground support facilities, a birth-to-death database per part number, models of failure and degradation, environmental hazards models, prognostics-based maintenance scheduling, and fleet-wide trending and data mining. Models and databases in the off-board component can be up-linked to the on-board IVHM component for model updates during flight. Included in our vision for IVHM is achieving a truly integrated approach to vehicle health management. This approach would effectively integrate aircraft data, health state data, and hazard data. Integration of aircraft data with health state data would enable diagnostic and prognostic reasoning that can adapt to aircraft state and flight conditions as well as phase of flight. Vehicle-wide integration of airframe, propulsion, and aircraft system malfunction, degradation, damage, and failure information would enable improved diagnosis and prognosis under coupled failure mechanisms. Integration of hazard information in diagnostic and prognostic reasoning would enable the IVHM system to account for deterioration in performance and/or expected useful life as a result of ice accretion, electromagnetic disturbances, and ionizing radiation. We believe that integration of aircraft data, health state data, and hazard information will enable more accurate diagnostics and prognostics with decreased false positive and false negative rates by accounting for aircraft state, flight conditions, coupled failure mechanisms, and environmental hazards during all phases of flight that could otherwise be misinterpreted. More details about this vision, and our plans to integrate IVHM technology development, are given in Appendices B and C. The realization of this vision will take a long-term research investment.

Toward that end, we plan to develop technologies to determine system/component degradation and damage early enough to prevent or gracefully recover from in-flight failures. These technologies will enable nearly continuous on-board situational awareness of the vehicle health state for use by the flight crew, ground crew, and maintenance depot. To achieve this, we will advance the state-of-the-art in on-board health state assessment to enable the continuous diagnosis and prognosis of the integrated vehicle's health status. One of our key contributions will be the incorporation of environmental hazard awareness with the more traditional electro/thermo/mechanical failure, damage and degradation mechanisms to more accurately assess the vehicle's health state. Another of our key contributions will be the sharing of information between the various vehicle subsystems to more accurately determine the health of both those subsystems and the integrated vehicle. All of our planned work supports the following three critical focus areas:

- Integrated continuous on-board vehicle health state assessment and management (detect, diagnose, prognose, and mitigate problems);
- On-board environmental hazard detection and effects mitigation (incorporate hazards into diagnosis and prognosis);
- IVHM system technologies (develop architectures to collect, transfer, and process data and tools to perform system-wide assessments).

Our approach is to:

- Develop and employ virtual and real sensors to assess subsystem states;
- Couple state awareness data with physics-based and data-driven models to diagnose degradation and damage caused by environmental hazards and electro/thermo/mechanical failures;
- Integrate sub-system information to provide diagnostics and prognostics for the integrated vehicle, including using data from one subsystem to provide information for another;
- Develop locally-controlled mitigation techniques to extend safe operation time; and
- Develop a public database and testing capabilities for IVHM technologies.

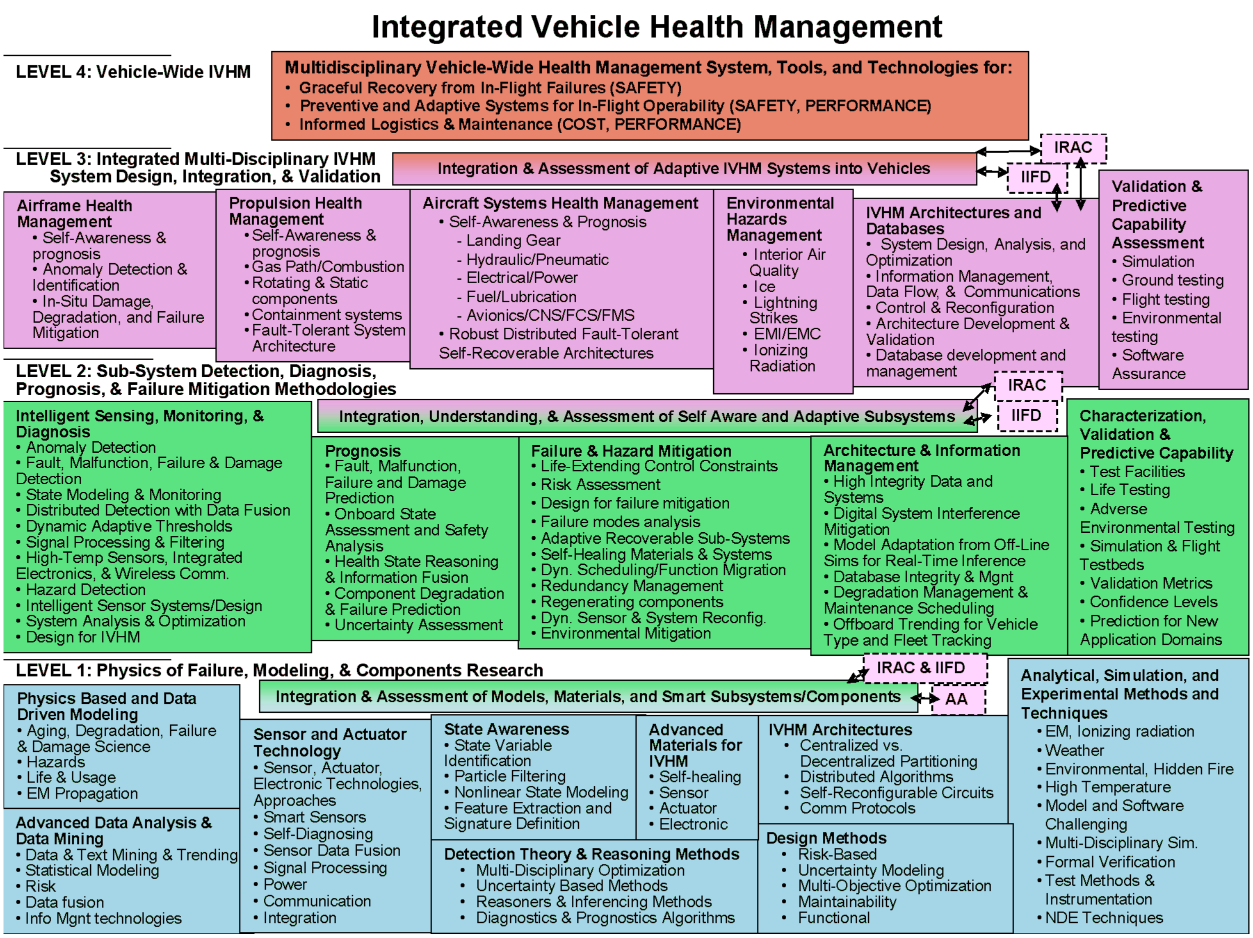

Figure 1: IVHM Level Diagram

To determine how specifically we could best contribute to advancing the state-of-the-art in these areas for maximum impact, we followed the process established by ARMD and solicited input from NASA's technical experts in the field of IVHM. That input was grouped into the key IVHM functions: detection, diagnosis, prognosis, mitigation, and system-level functions, and used as the starting point for determining the work that NASA is well qualified to do in IVHM. This input is shown in Figure 1A. From this starting point, we focused the roadmap to develop an IVHM Project plan, which represents only a fraction of activities identified in Figure 1A. Our focus process considered heavily the technologies that we considered essential for health management, past research experience and investment, and the available workforce. Examples of work that is important and relevant, but that we chose *not* to do based on constraints, include: 1) Developing specific damage and degradation models for engine components (blades, disks, shafts, seals, fittings, coatings, injectors, etc.) and incorporating them into 3D propulsion system simulators to determine global effects of local damage, 2) Developing high temperature sensors to detect the in-flight condition of the entire propulsion system, from the a Vehicles, and Next Generation Launch Vehicles. A bibliography of papers that were developed under these programs and that are being leveraged by the IVHM Project is provided in Appendix K.

Implicit in our focus process was knowledge of high-priority safety issues, and industry needs. It should be noted that, in this IVHM Project, we are leveraging a substantial body of prior work conducted under a variety of NASA programs, including: Aviation Safety and Security, Vehicle Systems, Advanced Subsonic Transports, Intelligent Systems, Collaborative Decision Systems, X-33, Reusable Launch Vehicles, and Next Generation Launch Vehicles. A bibliography of papers that were developed under these programs and that are being leveraged by the IVHM Project is provided in Appendix K.

We have focused our resources on specific tasks, each of which entails some combination of foundational research activities in modeling, data processing, sensor development, state estimation, detection theory and reasoning methods, materials, design methods, and experiments. These tasks are grouped into the three critical focus areas, which combine to develop the capability described above. The key challenges addressed in each are given in Table 1.

Focus Area	Task	Key Challenges Addressed
Integrated Continuous On-board Vehicle Health State Assessment & Management	Airframe	Detection: (i) Developing structural damage sensing technologies; (ii) Detecting damage in hidden locations; (iii) Developing self-powered wireless sensors. Diagnosis: Interpretation/assessment of sensor data to characterize structural health. Prognosis: (i) Developing computationally efficient methods to predict damage initiation and propagation, (ii) Incorporating diagnostic information to continuously update and correct predictions of damage propagation, residual strength and life of airframe structures. Mitigation: Developing structural materials capable of self-repair (healing) of incipient damage states.
	Propulsion System	Gas path: Adaptive on-board modeling to track gradual deterioration plus the ability to detect and distinguish abrupt or rapid engine performance events. Structures: Physics-based prognostics development for hot structures. Enabling technologies: High temperature sensors, electronics, and wireless communication technology.
	Aircraft Systems	Complex Electromechanical Systems: Developing diagnostics and prognostics that account for complex interactions between hydraulics, structures, and electrical components. Electrical Power Systems: Developing fault detection methods that can cover a broad range of continuous,

Focus Area	Task	Key Challenges Addressed
		discrete, and transient faults. Avionics: (i) Detecting, assessing, and mitigating the effects of soft faults at the LRU/LRM level; (ii) Developing approaches and methods for detection, diagnosis, prognosis, and fault isolation in complex, integrated, and interconnected avionics flight systems.
On-Board Environmental Hazard Detection and Effects Mitigation	Environmental Hazards Detection and Mitigation	Detection: Accurate location of iced aircraft state awareness, and electrical hazard prediction and detection. Mitigation: (i) Ice hazard assessment, (ii) Fault tolerant avionics to withstand ionizing and non-ionizing radiation
IVHM System Technologies	Architectures and Databases	Databases: Developing and maintaining detailed system and component performance and failure databases, and making them available across the industry for development of health management capabilities. Resilient Architectures: Developing design optimization and synthesis methods for IVHM architectures that are resilient to failures in the sensing, networking, and processing nodes.
	Verification, Validation and Predictive Capability	Analysis: (i) Methods to identify regions in a large and complex state space that correspond to marginal or unacceptable performance of IVHM systems; (ii) Methods to verify IVHM software. Simulation: (i) Guided Monte Carlo methods that explore marginal performance of IVHM technology in regions of the state space identified by analysis; (ii) Methods for simulation-based automatic test case generation, (iii) Methods for integration of flight, propulsion, and airframe structure simulations. Experimental Methods: (i) Hardware-in-the-Loop test capability and methods for validating integrated IVHM technologies; (ii) Defining requirements for in-flight sub-scale aircraft testing of IVHM technologies
	Systems Integration & Assessment	Integration: Implementing a capability to simulate and test many scenarios, quickly and cheaply Assessment: Implementing a capability to readily derive and aggregate cost, performance, and safety metrics for multiple combinations of IVHM components at various stages of technical maturity.

Table 1: IVHM Key Challenges

In the first five years, we will develop IVHM technologies in the three focus areas, as well as standard benchmark problems and metrics to evaluate health management system performance. This will give us confidence that the approaches that we have chosen are worthwhile for further development in the second five year period.   Other plans for the first five years are detailed in the milestone section, but a sampling includes:

- Techniques for on-board continuous assessment of structural health state, including detection through advanced sensor development, efficient diagnostic algorithms, prognostics with sensor data updates, and mitigation through self-healing materials and structures;
- Techniques for the on-board continuous assessment of aircraft gas-turbine engine gas-path state, including deterioration trend monitoring, and fault detection and isolation, and a wireless pressure sensor;
- Techniques for onboard continuous assessment of aircraft system health state including diagnostic and prognostics algorithms for complex electromechanical systems, electrical power systems, and avionics;
- Techniques for onboard detection and mitigation of engine icing, electromagnetic disturbances, and ionizing radiation;
- Design methods, architectures, communications protocols, and databases for distributed IVHM systems;
- Analytical, simulation, and experimental techniques, methods, and tools for verification and validation of IVHM technologies;
- Master simulation and experimental plan, metrics, and tools for assessing IVHM system safety and cost benefit.

Most of these technologies are long-term and are therefore intended for use in the next generation air transportation systems. Some will reach maturity sooner and will be relevant for the near-future air transportation system.   Technologies in the latter category include work in icing, where close collaborations with the FAA promise to integrate this technology into use quickly. We expect that much of the work in software V&V and radiation effects will have application for NASA's Exploration programs, as well as fundamental developments in detection theory and reasoning methods.

An example of the type of safety problem that we intend to address is asymmetric thrust, or a significant thrust mismatch between engines. If the aircraft is flying with auto-throttles and auto-pilot engaged, and the pilot is not diligent in monitoring cockpit indications, this is a fault type that can go undetected until the flight control system reaches it's operating limits at which time they disengage leaving the plane in an upset condition. This malfunction type has caused several fatal aircraft accidents in the past. Since it is often caused by throttle linkage problems, it may go undetected if monitoring is only done at the individual engine level. By combining information from several devices (automatic flight control throttle commands, onboard models of engine thrust response at the given power setting and flight condition, health status of the flight control computers and engine controllers, maintenance records on the throttle linkage, etc) it may be possible to reliably diagnose the fault. For example, a thrust estimate for each engine could be calculated by a propulsion health management function. Simultaneously, an aircraft system health management function could be monitoring the amount of flight control surface compensation the flight control computer is applying to keep the aircraft flying straight and level. Outputs from both health management functions could be fused to obtain more accurate detection of asymmetric thrust conditions. To determine an accurate thrust estimate, the propulsion health management function needs to monitor the state of the engine sub-components. The turbine blade tips may be eroded, causing inefficient growth in the tip clearances, for example, or the compressor efficiency may be degraded because of the accretion of glaciated ice. Similarly, the aircraft system health management function needs to monitor the state of the flight control system sub-components. For example, electromagnetic effects may have disturbed or damaged the flight controller, causing inaccurate control commands, or corrosion may have damaged a throttle or control surface linkage.

In addition, the airframe health management function would be monitoring structural loads associated with the asymmetric thrust conditions that could accelerate crack propagation, and would be performing onboard diagnostics and prognostics of critical structural components. The ability to monitor, communicate, and process distributed observations from disparate sub-systems and components would require an optimized and robust IVHM architecture.

We believe, and we intend to validate through benchmark scenarios, that: (1) a health management system that includes data from a variety of sources on the vehicle can determine system/component degradation and damage early enough to prevent or gracefully recover from in-flight failures; and (2) including hazard information into the diagnostics and prognostics improves the accuracy and robustness of onboard health state assessment. Such a demonstration requires the implementation of sensors and health state reasoning processes in propulsion, avionics, and airframe subsystems, the ability to introduce or emulate hazard conditions, as well as the fusion of data from these sources with aircraft maintenance records. This test, if implemented as a fully terrestrial distributed simulation, could possibly involve historical flight data, virtual sensors running at one Center, and models and simulated online diagnostics "devices" running at another. Software interfaces, protocols, and requirements traceable to the needs of a specific domain would be documented. A quantified assessment would be developed to estimate, for example, life cycle costs and benefits of implementing such a system on vehicle *X* after *Y* dollars are invested in closing remaining technology gaps *Z*. This example illustrates that, unlike the construction of a specific IVHM system for a specific vehicle, we intend to evolve toward an effective environment for assessing any aerospace IVHM technology.

We chose this example because it can incorporate "Level 1" developments in a variety of disciplines, including physics-based and data-driven modeling, sensor technology, advanced data analysis, state awareness, detection theory and reasoning methods, architectures, and experimental techniques. It also can employ the "Level 2" functions of sensing, diagnosis, hazard mitigation, information management, V&V, and system assessment. It ties together "Level 3" work in propulsion, aircraft systems, environmental hazards, airframe structure, architectures, V&V, and system integration. It can lead to a "Level 4" validation demonstration of integrated vehicle health management, which may be conducted virtually, or in representative NASA vehicles, or in industry testbeds that could potentially be provided by the many industrial RFI respondents.

1.2.1 Airframe Health Management

The inability to diagnose, prognose or mitigate damage in aircraft structures has been manifested in various forms, the most severe of which include catastrophic failure resulting in loss of life. Some well-known examples of catastrophic failure to passenger aircraft include: the loss of 18 feet of fuselage structure above the passenger floor after multi-site damage and crack link-up on an Aloha Airlines Boeing 737-200 in April 1988, the uncontained rotor burst of the left engine on a Delta Airlines MD-88 in July 1996, the failure of the composite attachment lugs on the American Airlines Airbus A300-600R in November 2001 and the fracture near the wing root on the Chalks Ocean Airways Grumman G-73T Turbo Mallard in December 2005. Each of these failures may have been prevented if a robust IVHM system had been in place at the time of the accident.

The effort in Airframe Health Management is focused on development of selected, but critical, fundamental technologies in three major areas: detection and diagnosis of damage; in-flight prognosis of damage; and mitigation of insipient structural damage. Within the area of detection and diagnosis, new sensors and sensory materials for determining the response states will provide input to computational algorithms that reconstruct damage fields from the sensor values. In the area of prognosis, the sensor data will be used to continuously update computationally efficient predictive algorithms for estimation of structural durability and life while the vehicle is in flight. Finally, in the area of damage mitigation, metallic and polymeric materials that incorporate healing phases will decrease the effects of damage and improve safety.

Unique NASA contributions to the Airframe Health Management element include: 1) world-class expertise in fracture mechanics, computational mechanics, material synthesis and characterization, and development of integrated multifunctional lightweight sensors; 2) extensive experience in application of emerging technologies to address critical issues (i.e., failure and incident investigations); and 3) unique facilities available for research on advancing the state-of-the-art in these areas.

1.2.1.1 Detection and Diagnosis

One vision of an in-flight IVHM system incorporates lightweight, low-power, rugged, and highly reliable sensors that can monitor thousands or even millions of measurement points. These unprecedented levels of detection might reveal structural damage sufficiently early to prevent catastrophic events, and provide vehicle state awareness data to provide true prognostic capability. To achieve this vision, we must develop new sensors, sensory materials, and techniques for interpreting the sensor data to diagnose structural damage initiation and propagation. Even IVHM concepts less reliant on vast sensor arrays will benefit from the development of these technologies.

1.2.1.1.1 Detection – Development of Advanced Sensors

Multiple new sensor technologies will be developed to locate and identify damage, including: optical fiber-based sensors, micro-electromechanical systems (MEMS) and nanotechnology-based sensors. New robust and reliable techniques will be developed to embed emerging optical fiber-based systems, with thousands of sensors per fiber, into airframe structures. Optical fiber-based sensors including photonic crystal fibers, and micro- and nano-structured fibers will be developed for multifunctional sensing of strain, temperature, acceleration, vibration, acoustic waves (both for passive and active interrogation), chemical sensors to detect corrosive environments or corrosion byproducts, or leaks from hydraulic or fuel systems, etc. MEMS- and nanotechnology-based sensors will enable intelligent, autonomous distributed sensor systems that use little power, are lightweight, and can operate in harsh environments. These sensors will be capable of measuring strain, temperature, pressure, damage and aggressive or corrosive environments. Carbon nanotube-based strain sensors will be developed and embedded as part of a composite material system to provide three-dimensional strain mapping with high sensitivity and spatial resolution.

The need to reduce sensor size and weight provides opportunities for distributed and/or wireless sensor networks with self-powered or energy harvesting capabilities. Distributed computing provides for sensor located data processing to reduce network bandwidth, validate sensor data and integrity, and standardize data formatting and reporting from numerous sensor types and parameters. Advances in energy harvesting will enable sensors to interrogate the structure without heavy and unreliable wiring to provide power.

1.2.1.1.2 Detection – Development of Sensory Materials

Sensory metallic materials are structural metallic materials that contain a small weight percent of either engineered second phase "sensory" particles or nano-scale sensors. Because of their very small size and ubiquitous placement, the sensory particles allow detection of incipient damage and detection of damage in previously hard to inspected locations. These sensory microstructures must be designed so that the state of the particles accurately represents the state of the surrounding structural material. Emerging computational technologies such as discrete atomistic simulations and various continuum mechanics-based micromechanics analyses can be used for design of these materials. Additionally, advances in the processing and testing of both the mechanical and sensory response of prototype sensory microstructures are also needed. Many of the fundamental damage science tools and experimental techniques required for development of sensory metallic materials will be developed in conjunction to advances made under the Aircraft Aging and Durability project.

1.2.1.1.3 Diagnosis – Interpretation of Sensor Data

Diagnostic tools for interpretation of the output from the various new sensors will be integrated within an IVHM system for monitoring the initiation and propagation of structural damage. Developments will include: new techniques that facilitate processing of sensor data; incorporation of optical frequency-domain reflectometry (OFDR) into fiber-based diagnostic systems; an inverse finite element method (iFEM) that computes field response quantities from point values; and electrical impedance damage detection (EIDD) methodology that uses neural networks to obtain an inverse solution based on electrical conductivity mapping.

Techniques will be developed to facilitate demodulation, processing, and integration of advanced, lab-emergent sensor suites from thousands or millions of sensors within a diagnostic system for quasi-static and dynamic loadings. Additionally, new algorithms for diagnosis of structural health using sensors in surface and embedded distributions will be developed. The accuracy, dynamic range, and data rate capabilities of existing fiber-optic based structural shape sensing technology will also be evaluated and a computationally efficient fiber Bragg grating interrogation technique will be integrated into existing OFDR technology for high speed structural shape sensing.

Two types of inverse methods, which can be used independently or conjunctively, will be developed to diagnose damage throughout the structure. iFEM is being developed for in-flight reconstruction of continuous field quantities from point measurements determined by sensors at many discrete locations. Advances in the methodology will include the ability to interpret response under complex loading and geometric nonlinearities; and the ability to determine the location and mode of damage in both metallic and composite structures. EIDD is based on electrical conductivity mapping and inverse methods and has shown promise as an alternative approach to diagnosing the state of internal damage. In EIDD, a methodology rooted in medical imaging techniques, in-situ electrical resistance measurements of a conductive or partially conductive material are input to an artificial neural network or other inverse algorithm that has been trained *a priori* based on finite element models of electrical resistance using heat transfer models. The computed inverse solution allows both the location and magnitude of structural damage to be quantitatively estimated from these resistance measurements in near real-time.

1.2.1.2 Prognosis

Prognosis is defined here as in-flight prediction of future damage states from the current diagnosed state. The prognosis methods can be interpreted to determine locations requiring more intensive ground-based Non-Destructive Evaluation; time until the next required maintenance; remaining life of the Airframe; and, in conjunction with the Integrated Resilient Aircraft Control (IRAC) project, airworthiness of the structure after discrete source damage. Of particular interest is development of computationally efficient algorithms suitable for use in flight, including the development of techniques to enhance the accuracy of predictive algorithms through integration of sensor data.

1.2.1.2.1 Prognosis – Computationally Efficient Damage Growth Algorithms

Predictive methods suitable for estimating damage growth and residual life of structural components during flight and in the presence of multiple arbitrary damage sites require both accuracy and unprecedented computational efficiency. Among the candidates for satisfying these simultaneous requirements are the Extended Finite Element Method (X-FEM) and the response surface method based on prior rigorous solutions. X-FEM is a new and promising formulation that implements a discontinuous function combined with asymptotic crack-tip displacement fields to enable the domain to be modeled by finite elements without explicitly meshing the crack surfaces. Thus, the location of the crack discontinuity can be arbitrary with respect to the underlying finite element mesh, and quasi-static or fatigue crack propagation simulations can be performed without the need to remesh as the crack advances. Less elegant, but more well established, than the X-FEM, a predictive methodology based on response surfaces tuned to represent computationally intensive finite element solutions, will allow very rapid interrogation of the damage state. Since the response surfaces can address only cases that have been previously considered via detailed analyses, the specific parameter space for their construction must be considered very carefully.

1.2.1.2.2 Prognosis – In-Flight Integration of Sensor Data with Predictions

The most credible, and often most accurate, analyses are those that have been validated using experimental data. Similarly, continuous in-flight correction of damage state predictions by integrating sensor data will ensure the validity of the in-flight prognosis. In the integrated prognosis approach, inverse methods (to obtain current states) and forward methods (to predict the future behavior) will be combined with Probabilistic Risk Analysis (PRA), to account for uncertainties in measured and computed values) to provide in-flight estimates of both the life of the Airframe and the confidence in those predictions. Bayesian estimates, various statistical methods, and neuro-fuzzy methods will be considered for inclusion as part of the PRA.

1.2.1.3 Damage Mitigation

Mitigation involves either the restoration of some or all of the load-bearing capability of a structure under monotonic loading or the reduction in the rate of damage accumulation under cyclic loading. Materials that are capable of self-healing incipient damage states will be of great benefit in environments and conditions where access for manual repair is limited or impossible or where damage may not be detected. Structures made of either healing metallic or healing composite materials may have significantly prolonged service life and improved safety and reliability. New design and analysis methodologies will be required to fully exploit the benefits of both types of healing material systems.

1.2.1.3.1 Mitigate – Development of Healing Metallic Materials

Healing metallic materials are structural metallic materials that incorporate a secondary healing phase or coating. The healing quality - the extent to which the initial mechanical properties of the metal can be restored or the degree of fatigue damage suppression - depends not only on the mechanical properties of the healing material, such as strength and toughness, but also on the interface between the healing material and the structural material. Various candidate healing material-structural metallic material systems will be interrogated to determine the optimum material combinations for both strength-critical and fatigue-critical conditions. Emerging computational, experimental and processing technologies will be used to design and manufacture the materials for optimum damage mitigation.

1.2.1.3.2 Mitigate – Development of Healing Composite Materials

Healing composite material systems rely on an appropriate combination of viscoelastic matrix properties so that the energy induced by the damage liquefies and flows the matrix. While many advances have been made toward optimization of the fundamental properties of the matrix material, much work remains to develop corresponding composite material systems in which the self-healing capabilities of the matrix suppress delamination and matrix cracking. Advances will include development of cost-effective processing methods for mass production of self-healing matrix materials; optimization of the matrix-fiber interface properties; optimization of processing methods to make the self-healing matrices amenable to integration into a functional composite system; and characterization of the properties of the new material systems.

1.2.2 Propulsion Health Management

Aircraft engines are highly complex systems consisting of static and rotating components, along with associated subsystems, controls and accessories. They are required to provide reliable power generation over thousands of flight cycles while being subjected to a broad range of operating loads and conditions, including harsh high temperature environments. Over repeated flight cycles the life of many engine parts will be consumed, and engine malfunctions may occur.

Past advances by NASA, industry, and the DoD have resulted in Propulsion Health Management (HM) capabilities that assist operators in monitoring and managing their engine assets. Under the IVHM project, NASA will continue to focus on enabling propulsion HM technology that complements the ongoing research of other organizations. NASA's unique contributions will include: on-board adaptive model technology specifically tailored for diagnostic applications, prognostic techniques to address localized softening mechanism effects on hot structural life, integration of propulsion and aircraft health information for improved vehicle-wide state-awareness, and high temperature wireless sensing and communication technology. Research in these areas will advance the state-of-the-art in propulsion system detection, diagnosis, and prognosis. For the scope of this technical plan summary, mitigation strategies will be limited to providing data for use by the FADEC and/or on-ground maintenance crew.

1.2.2.1 Propulsion Gas-Path Health Management

Effective engine gas path health management (GPHM) techniques are required to manage the health of engine flow path components, control sensors, and control actuators. These techniques must possess the necessary robustness to reliably function over a broad range of engine operating environments and condition levels. An emerging GPHM approach is model-based diagnostics which has been enabled by the inclusion of on-board self-tuning models on some newer production aircraft engines. The development and maturation of on-board engine model technology has been achieved through past investments by NASA, DoD, and industry. Model-based diagnostics enables more accurate performance baselines to be established for individual engines thus facilitating more accurate fault diagnostics. They also enable the model-based estimation of unmeasured parameters critical for IVHM.

Under the IVHM Project NASA will first develop standard gas path diagnostic benchmark problems and evaluation metrics. This will include a variety of fault types, magnitudes, and signatures occurring over a variety of operating conditions and engine deterioration levels as defined in previously published literature and operational data. Emphasis will be given to propulsion malfunctions which are known contributors to aviation accidents, particularly propulsion system malfunction plus inappropriate crew response accidents. The benchmark problems will be simulated using the Modular Aero-Propulsion System Simulation (MAPSS), a generic NASA turbofan engine simulation for controls and diagnostics research and development applications. The benchmark problems will be suitable for use in establishing the baseline performance of published gas path deterioration trending and fault detection approaches. These benchmark problems will serve as a platform to evaluate new approaches developed by NASA under the IVHM project. A version of MAPSS and the benchmark problems will be provided to NRA partners, and will also be made available for integration into the NASA agency-wide IVHM test bed.

In the areas of GPHM trending and detection NASA will specifically focus on developing adaptive on-board modeling technology with the ability to track gradual deterioration plus the ability to detect and distinguish abrupt or rapid engine performance events. This challenge must be addressed to avoid the scenario of fault signatures being absorbed into the adaptive model updates. We will coordinate this effort with related work on-going within industry and the DoD, particularly in the area of Model-Predictive Control. NASA will also focus on the development and evaluation of transient fault detection approaches. Conventional GPHM approaches primarily process quasi-steady state data. However, certain fault types are more readily observable during transient operation. The integrated performance of the new GPHM trending and detection technology will be evaluated using the established benchmark problems and metrics. Furthermore, we will demonstrate the benefit of incorporating NASA-developed propulsion HM sensors (described below) within a gas-path health management system.

1.2.2.2 Propulsion Structural Health Management

Structural life is extremely sensitive to preexistent damage such as manufacturing flaws and/or service induced damage that can cause immediate fracture or serve as sources for early fatigue cracking. Current propulsion structural life management approaches rely on a combination of predictive models and periodic inspections both on-line and off-line. The approaches primarily in use today are: 1) Safe-Life Design - requires that the component be retired before the initiation of cracks and is susceptible to the presence of unanticipated structural or material damage that greatly reduced the crack initiation portion of the fatigue process; 2) Damage Tolerant Design - assumes a structure contains initial cracks (typically assumed equal to the largest undetected defect size), and defines the ability of the structure to resist fracture from cracks of a given size for a specified time period; and 3) Retirement for cause - utilizes periodic inspection intervals to locate damage components that are then either repaired or replaced. The inspection intervals are based on the time for an undetected crack to grow to fracture. All three approaches demonstrate the *interdependence* of diagnostic (inspection) and prognosis (life prediction) methods and stress the importance of developing the fundamental scientific causal relationships of failure in order to provide the key diagnostic/prognostic linkage for different material systems and structures. Large improvements in safety, life extension, and overall life costs can be attained by a new philosophy to propulsion health management: A two-pronged approach that links complementary diagnostics (i.e., detecting and accurately grading damage in real time) and prognostics (i.e., calculating remaining life) for structural life management. Only when these two views are consistently integrated (the connecting link being the current state of the material/structure, i.e., state awareness) can a rational and viable life management system be established for propulsion structural components.

Under the IVHM Project NASA will focus on critical prognostic challenges associated with hot structural life management (i.e., induced localized softening mechanisms which are strongly influenced by geometry, loading conditions, inherent defect distributions, material anisotropy). The work will consist of physics-based prognostics methodology development, characterization and experimental validation. Structural finite element based simulations will be performed and evaluated using a multi-mechanism viscoelastoplastic deformation model coupled with continuum based stiffness and strength degradation damage parameter. Note, the time dependent aspect of the model (i.e., viscoelastic and viscoplastic) will only dominate at elevated temperatures. Appropriate local and global failure criteria will be identified. The physics-based prognosis methodology will be established for high temperature static (non-rotating) structural components under general loading conditions (multiaxial loading with and without overloads, cyclic effects, thermomechanical, etc.) and experimentally validated with the design of a prognostically challenging test matrix. This test matrix will consist of bi-axial experimental demonstration problems at ambient and elevated temperatures that will be suitable for use in characterizing, evaluating and ranking both detection and prognostic methods. Finally, given the experimental results, probabilistic measures to account for uncertainties will be identified and documented.

1.2.2.3 Propulsion Condition Assessment via Integrated Propulsion and Aircraft Measurements

Some propulsion system faults are not directly observable by monitoring the individual engine parameters in isolation. For example problems with stuck throttle linkages will result in the FADEC controlling the engine to a thrust setting different than that commanded by the pilot or automatic flight controls. At the engine level this problem will not be apparent, as all measurements will appear nominal. Detection of such faults requires the monitoring of measurements from all engines and the aircraft in an integrated fashion, and leveraging the principle that changes in aircraft propulsion system performance directly affect overall vehicle flight response characteristics.

NASA will develop an integrated airframe and engine sensor suite that can detect and isolate individual engine performance shifts. This will include the development of "virtual sensors" when instrumentation hardware is not practical to use. Examples of a virtual sensor include engine thrust and vehicle performance estimates. Techniques will be developed and validated in a simulation environment utilizing aircraft models and the MAPSS engine model. This work will leverage past NASA advances under the Propulsion Controlled Aircraft program and the C-17 IVHM-related flight research activities, and will be coordinated with propulsion and airframe control optimization efforts planned under the NASA Subsonic Fixed Wing Project in the Fundamental Aeronautics Program. This work can also be applied to and benefit the Supersonics, Hypersonics and IRAC projects, and the Airspace Systems Program.

1.2.2.4 High Temperature Sensors, Electronics, and Communications

A critical first step in any health management process is the acquisition of physical system measurements via sensors and communication architectures. State-awareness is the foundation of prognostics, and present aircraft propulsion systems have limited self-awareness. Opportunities exist to develop new sensors, particularly in engine hot-sections, to increase the accuracy of predictive methods. Combined with the models and reasoners described above, the development of intelligent system hardware including sensors, processing electronics, communications, and power scavenging operable within engine hot-sections will provide fundamental technology that will be of use to developers of health management systems for commercial, military, and space applications. NASA is uniquely qualified to conduct technology development in these areas.

The number of potential high-temperature sensors is large. Industrial response to the NASA RFI in IVHM yielded requests from several companies and consortia for NASA to develop high-temperature, low-weight, wireless, low-cost, durable sensors for a wide variety of applications including: gas-path and structural temperature mapping; dynamic pressure, temperature and strain for the combustor, augmenters, and turbine, and rotating components; chemical species for emissions and degradation; vibration and blade health sensors; and structural crack, damage, and load monitoring sensors.

Given our resources, we have chosen to focus our sensor development technologies in three primary areas: 1) high-temperature pressure sensors for incorporation into gas-path trending and fault diagnostic models to infer turbine health, 2) structural health monitors including smart accelerometers, and optical strain and blade tip-timing sensors, and 3) high-temperature wireless communications and energy harvesting technologies to enable the addition of these high-temperature sensors while minimizing wiring and power requirements on the engine. In each of these areas we will be focusing on generating the fundamental knowledge required to permit end-users reliable access to this technology for incorporation into their own systems. Emphasis will be placed on understanding the fundamental physics of devices at temperatures up to 500 C. SiC, piezoelectrics, and optical fiber sensors will be investigated. SiC will also be assessed for active electronic components, and energy harvesting will focus on developing thermo-electric-voltaic and photo-voltaic materials for generation of power for remote sensors.

1.2.3 Aircraft Systems Health Management

Aircraft systems play a critical role in aircraft safety, reliability, and mission success. Failures may result in flight delays, cancellations, safety-related incidents such as airspace violations, and major incidents and accidents. As such, Aircraft Systems Health Management is a key element of Integrated Continuous On-board Vehicle Health State Assessment & Management, one of the three critical focus areas of the IVHM project.

The vast number of life-limited subsystems, components, and unique parts that need to be covered across the industry is a significant challenge for aircraft systems health management. Given the relatively low cost of some of the aircraft subsystem components, it is often cheaper to use these systems until they fail and to replace them without further troubleshooting, assuming that there will be enough redundancy or performance margin to maintain safety. However, that assumption sometimes fails to hold and simple failures of aircraft subsystems may yield catastrophic results (e.g., Helios Airways B-737 crash in Greece in 2005 (depressurization); Aeroperu B-757 crash in 1996 (blocked static ports)). In addition, as the CAST study mentioned earlier indicates, landing gear problems are the second largest cause of accidents due to aircraft system or component failures.

The objective of this research element is to develop health management technologies, methods, and tools pertinent to safety-critical aircraft subsystems, assemblies, and components. The scope of this effort includes hydraulic and pneumatic systems, electrical power systems (EPS), electrical wiring, fuel and lubrication systems, avionics, and software. Systems that are specific to military applications (such as weapon systems or low-observability systems) are outside the scope of this particular research effort. Research challenges in aircraft systems health management include:

- Failure modeling, prognostics, and life estimation for electronics;
- Modeling, diagnostics, for prognostics for complex, integrated electromechanical systems;
- Software health, safety, and failure containment;
- Verification and validation of diagnostic and prognostics models;
- Sensor fusion and sensor validation for suppression of false alarms;
- Fault-tolerant architectures and automated fault management techniques.

We plan to focus our research on three specific areas: complex electromechanical systems, EPS, and avionics (including flight controls). These areas were selected on the basis of safety criticality, availability of unique NASA expertise, and industry demand. Furthermore, in selecting these research areas, we aimed to minimize overlap with the ESMD ISHM project and to prioritize work that has dual-use applicability to ARMD as well as space exploration missions. Specifically, the ESMD ISHM project performs complementary work on power system diagnostics and prognostics, built-in-tests for avionics, and GN&C component prognostics. The two projects will continue to coordinate their activities during the execution phase of the AvSP.

The resources and expertise required for the research element resides in participating NASA centers. Unique NASA contributions to the Aircraft Systems Health Management element include: 1) world-class intellectual property in fault detection, diagnostics, and prognostics methods and technologies; 2) substantial domain expertise in electrical power systems, electromechanical systems, and avionics health management; and 3) unique facilities available for research on advancing the state-of-the-art in these areas. Specifically, ARC has substantial expertise in fault detection, diagnostics, and prognostics technologies with applications in EPS components, wiring fault detection, and prognostics for Guidance Navigation and Control components. GRC has substantial expertise in diagnostics, prognostics, and automated failure management for EPS and electromechanical actuators. LaRC has substantial expertise in avionics health management including diagnostics, prognostics and failure mitigation, embedded electronics with built-in test and fault recovery, and distributed diagnostic infrastructures for multiple and/or redundant aircraft systems. Additional capabilities in sensing, diagnostics, and prognostics for aircraft systems will be provided by academia and industry under guidance from NASA. Available NASA facilities include the Advanced Diagnostics and Prognostics Testbed (ADAPT) at ARC, the Power Management and Distribution testbed at GRC, the Aircraft Landing Dynamics Facility (ALDF) at LaRC, and the Systems and Airframe Failure Emulation Testing and Integration (SAFETI) Lab at LaRC. Research activities under this research element will be tightly coordinated with other similar activities funded by the U.S. Government. In particular, we will coordinate activities with NASA's Exploration Technology Development Program ISHM Project, DARPA Prognosis program, AFRL ISHM Architectures program, and the NAVAIR and AFRL SBIR programs. We will also coordinate with the leading aircraft diagnostics, prognostics, and health management activities in the DoD and industry, including the F/A-22, F-35, C-17, V-22, B-777, and B-787. Finally, we will engage the industry and academia through Space Act Agreements and NASA Research Awards (NRA). The resulting methods and tools will be made publicly available to assist the aerospace community in demonstrating compliance with safety regulations.

1.2.3.1 Diagnostics and Prognostics for Complex Electromechanical Systems

Precursors to catastrophic system and component failure may involve subtle and complex interactions between hydraulics, structures, and electrical components. R&D challenges for electromechanical system health management include diagnostics for complex sub-system interaction, sensor fusion, and validation of IVHM technologies in high-fidelity relevant environments. The work on electromechanical systems health management will expand upon the work initiated under the NASA Aviation Safety (AvSP) I program for diagnosing faults in commercial aircraft landing gear.

Failures of electromechanical systems such as flight controls, landing gear, thrust reversers, and cargo/cabin doors are a major contributor to aircraft accidents and incidents. We will ground our research activities in a few selected electromechanical systems of varying complexity. On the simpler end of the spectrum, we will develop methods for diagnostics and prognostics using a flight control actuator. As these methods and tools are matured, we will transfer and deploy them on a more complex, flight-like hardware-in-the-loop test platform based on a B727 landing gear. Specifically, we will extend the ADAPT lab at ARC with a hardware-in-the-loop actuator diagnostic element. We will further mature these diagnostic and prognostic technologies through full-scale landing gear experiments with seeded faults and failures. The Aircraft Landing Dynamics Facility (ALDF) at LaRC is a test facility capable of exercising a landing gear, for a brief extent, through the touchdown, rollout, and braking phase of aircraft landings at operational load and speed conditions. The experiment design entails subjecting a Boeing 727 main gear to loading conditions representative of takeoffs and landings while injecting sub-system failures representative of those observed in flight operations.

We will develop concepts for identifying degradation trends and / or anomalous conditions using physics-based, data-driven, and statistical approaches. We will design and develop Bayesian sensor fusion tools for robust state estimation as well as to distinguish sensor failures from true failures. We will use the actuator testbed to detect performance degradation and to develop models for estimating remaining life of actuators. We will also develop model-based diagnosis tools to detect and isolate failures on the B727 landing gear during experiments at the ALDF. We will collect and analyze experimental data in order to develop prognostic models for landing gear components prone to mechanical wear. Finally, we will develop and demonstrate benefits gained through extending existing data sources with retrofit sensors (fiber optic, wireless, etc.).

1.2.3.2 Electrical Power System Diagnostics and Prognostics

Electrical power systems (EPS) have an increasing critical role in today's fly-by-wire aircraft. While a Piper Cub can perfectly fly around the world without a functional EPS, a pervasive EPS failure can disable a modern transport aircraft. Furthermore, EPS components are distributed throughout the aircraft and contribute to substantial maintenance costs. Finally, EPS are designed with substantial redundancy due to the high risk of component failure, thus contributing to increased aircraft weight and fuel costs. As a result, diagnostics and prognostics for EPS components is an important research topic in aerospace applications.

One of the challenges in EPS health management is that signals and faults manifest themselves in continuous, discrete, and transient domains. Thus, no single fault detection methodology is sufficient to cover a broad range of EPS failures. Incidentally, this makes EPS an ideal testbed for the development of hybrid reasoning methods based on continuous and discrete models of a physical system. The Advanced Diagnostics and Prognostics Testbed (ADAPT) at ARC is designed for hardware-in-the-loop diagnostics and prognostics applications. Although it is not specific to EPS health, ADAPT includes an EPS designed to represent many modern aircraft and spacecraft EPS configurations and to replicate many fault modes including continuous faults (e.g., battery discharge), discrete faults (e.g., failed power supply), or transient faults (e.g., intermittent contact across a corroded switch).

During the course of this project, we will use the ADAPT testbed to develop Bayesian sensor fusion tools for robust state estimation and sensor failure detection. We will also use ADAPT to further develop and refine model-based and hybrid diagnosis tools such as ARC's Hybrid Diagnosis Engine (HyDE).

1.2.3.3 Avionics Health Management

Aircraft Flight Control Computers (FCCs) are typically implemented with redundant processing elements in order to mask random independent component failures, or hard faults. However, redundancy alone does not mask the effects of soft faults. Soft faults can result in a malfunction at the system level without any components in the system being damaged or failed. Soft faults are often produced by common-mode disturbances (such as lightning and High-Intensity Radiated Fields (HIRF)) that can affect the functional integrity of all processing channels during the same event. During flight, malfunctioning systems can be taken offline by the pilot, or disengage themselves under certain conditions. There is currently no standard approach for managing system level malfunctions caused by soft faults in avionics flight systems, other than to pull the LRU (Line-Replaceable Unit) off of the aircraft for testing after the flight. Testing of LRUs that have malfunctioned as a result of soft faults typically results in an inability to find any failed components. As system complexity and the flight criticality of functions performed by such systems continue to increase, the ramifications of in-flight malfunctions and the need for IVHM technologies for flight critical avionics will increase. Under the NASA AvSP 1 Program, an approach was developed for monitoring functional integrity in control computers with redundant processors. The developed approach is based on a multi-stage detector that utilizes distributed detection methods with decision fusion. The detector was demonstrated using data from a quad-redundant flight control computer that was subjected to HIRF during closed-loop laboratory experiments for the purpose of characterizing the functional effects. Experimental data shows that HIRF-induced malfunctions in this controller are nonlinear and non-Gaussian. The performance of the detector was evaluated empirically in terms of false positives and false negatives with very promising results. Under this project, we will improve this monitoring approach and adapt it for online implementation and performance evaluation during closed-loop HIRF experiments. We will also develop analytical models of the FCC and the associated disturbance effects, as well as analytical methods for assessing detector performance.

The multi-stage detection approach described above was developed for avionics function monitoring at the LRU level. However, commercial aircraft rely on complex, integrated, and interconnected avionics flight systems (including the flight control system, navigation system, and guidance system) that are interfaced at the LRUs. There is currently no aircraft-wide approach for ensuring the integrity of these systems or to contain faults generated in one system and prevent them from propagating into interconnected systems. In this project element, we plan to develop an approach for aircraft-wide monitoring and management of the integrity of complex, integrated, interconnected avionics systems. We will also seek to develop approaches and methods to contain faults and prevent propagation into interconnected systems. The methods to be included in the approach are to be determined, but may include function monitoring, fault detection and identification methods, data mining and information fusion from available aircraft data, cross-correlation between similar measurements, signal and parameter estimation, and feature extraction, as well as other methods. We will utilize the state-of-the-art distributed flight control system and flight management system that is currently integrated with cockpit systems and flight simulation available in the SAFETI Lab. We will also develop physics of failure methods and prognostic models for avionics and electronics. This work will be conducted collaboratively at the ADAPT testbed and the SAFETI Lab.

Participation of NRA awardees and SBIR partners is anticipated in the development of these IVHM technologies for avionics.

1.2.4 Environmental Hazard Management

The health of an aircraft system is significantly affected by a variety of on-board hazards associated with aircraft environmental systems. In fact, these hazards are a significant component of the safety issues, fatal or otherwise, present in today's commercial fleet. An environmental hazard is an effect due to conditions surrounding or interior to a vehicle that causes damage or degradation in the operation of the aircraft including catastrophic failures. Technologies to manage degradation, damage, and failures caused during nominal aircraft operation are covered in the airframe, propulsion, and aircraft systems sections. Degradation, damage and failures caused by mechanisms that are not expected to exist under nominal operations are covered here. These hazards come in two classes: those originating off-board (but causing on-board problems) and those originating on-board. The former class includes lightening, ionizing radiation, High-Intensity Radiated Fields (HIRF), and icing; the latter includes electromagnetic interference.

NASA has a long history and world recognized expertise in addressing a range of Environmental Hazard technical problems. For example, in the 1980's, foundational work was done in lightning research through the F106B thunderstorm research program on which current lightning certification requirements are based. NASA research in icing has been an industry standard for understanding and mitigating the hazards of aircraft icing. NASA is pioneering understanding of the effect of neutron bombardment on avionics control systems operating at high altitudes. NASA unique facilities include the NASA SAFETI and HIRF Labs, Icing Research Tunnel (IRT), and the Microsystems Fabrication Laboratory. Given this history and set of capabilities, the range of problems being addressed in this task are directly in line with existing NASA core competencies and capabilities. In each case, the tasks are not being addressed elsewhere to our knowledge; in fact, in multiple Environmental Hazard areas, NASA expertise is requested by the FAA and/or industry to help solve safety related problems.

1.2.4.1 Icing

Significant safety problems such as loss of control accidents in super-cooled large droplet icing conditions and engine power loss events due to high ice water content encounters continue to occur. The FAA has asked NASA to specifically address these liquid water and glaciated ice conditions and their effects on aircraft.

Due to high-density air traffic and controlled airspace routing, encounters with glaciated icing can occur in convective weather, specifically thunderstorm anvils and tropical convergence zones. Meteorological conditions within these weather systems can cause the formation of ice within engine compressor and booster stages, resulting in power loss. Similarly, super-cooled large droplets (liquid water) have caused recent concerns due to ice formation aft of conventional ice protection limits. This generates operational conditions outside of the current certification design standards. The fundamental physics of these icing conditions and their operational hazards are not well understood.

Our plan is to develop instrumentation for making research-quality measurements, characterize ice crystal conditions in meteorological systems where engine power loss events have taken place, assess aircraft state to classify hazard levels for mitigation strategies, and produce a database for use by the FAA and the Original Equipment Manufacturers. This includes both airframe and engine state monitoring for icing effects and ice crystal/mixed phase conditions and flight-testing to evaluate icing-induced performance degradation.

1.2.4.2 Ionizing Radiation

The issue of atmospheric induced Single Event Effects (SEE) is particularly vexing for electronic systems for commercial aviation. Such systems are based upon the application of commercial off the shelf electronic devices. These types of devices are designed for the large consumer market where there is no qualification requirement for operation in a radiation environment. However, it is known that SEE phenomena have affected operation of the overall aircraft electronic system. A principle SEE threat is atmospheric neutrons. Since it is not economically feasible to harden commercial aircraft avionics from neutron induced SEE, mitigation strategies that include a combination of recovery and redundancy are needed.

Several experiments were conducted by NASA (in collaboration with the Los Alamos Neutron Science Center, Honeywell, Old Dominion University, and the FAA) to analyze the effects of neutron bombardment on avionics control systems operating at altitudes where single event effect rates on electronics are on the order of 100 to 1000 times greater than at sea level. It is believed that mitigation techniques such as rollback recovery that were developed for mitigating lightning and HIRF effects under the NASA AvSP I Program can be extended to include mitigation of SEE phenomena.

The expected benefit of this research will be the development of design and validation guidelines for the cost effective achievement of aircraft system performance in the atmospheric neutron environment that provides the degree of safety needed for critical aircraft functions. Technical activities include the following: 1) Utilization of SEE data to validate statistical models that predict the performance effects of roll back recovery strategies, and analyze their effectiveness; 2) Design and development of a simple FCC which uses a combination of redundancy, recovery, and radiation hardened components and 3) SEE testing of the newly developed system for assessment of the fault tolerant controller effectiveness and robustness to atmospheric neutrons. Since such a system would be completely known and non-proprietary, it would be ideal for conducting fundamental research in fault tolerant systems from which detailed results could be widely published.

1.2.4.3 Lightning and Electromagnetic Interference

The interaction of the electromagnetic environment with advanced IVHM sensor technologies is important to the success of the IVHM objective. Tomorrow's aerospace vehicles will utilize embedded wireless sensors, new communication navigation and surveillance radio technologies, onboard wireless local area networks, intra-airplane data networks, advanced composite materials and a host of other new technologies. These new technologies must be protected against the damaging effects of direct and indirect lightning strikes and electromagnetic interference (EMI). New methodologies will be developed in this program for Lightning/EMI hazard management.

The determination of the effects of lightning on aircraft operation is based on many years of ongoing investigations. More recently, the potential risk of Portable Electronic Devices to interfere with aircraft navigation and communication radio receivers has been identified. The FAA and other air-worthiness certification authorities have guidelines and standards for both lightning protection and EMI for conventional aircraft. It is expected that this research will provide valuable information for the improvement and modification of these guidelines.

The technical challenges addressed in the IVHM project include the creation of new measurement methods to characterize EMI, lightning effects, and pulsed, burst and UWB emitters on embedded and wireless sensors, flight critical systems, and advanced composite materials. In addition, new computational methods and analysis tools will be developed to optimize designs before manufacturing and reduce reliance on post manufacturing measurement. This effort will develop computational and empirical techniques to enable the prediction of performance and compatibility of on-board IVHM systems and identify installation & design factors that may impact electromagnetic compatibility with other onboard systems.

1.2.4.4 Integrated Technology Efforts

As seen above, the technical response to a hazard is often very specific to that hazard. Nonetheless, there is interplay between the various hazards. The IVHM project has identified multiple areas where the various task and Centers can possibly combine activities to produce an improved and more comprehensive IVHM system, such as:

- **Laboratory Testing of Sensor Networks:** Even a properly designed wireless system will encounter unforeseen issues upon installation in an aircraft. NASA LaRC and GRC will test a wireless sensor network for Lightning & HIRF immunity and radiated emissions with the NASA SAFETI and HIRF Labs. NASA LaRC will provide electromagnetic environment test facilities and engineering expertise to the testing of prototype sensor networks. This testing will allow the NASA GRC development team to identify weaknesses and faults in these sensor networks, and facilitate development of algorithms for diagnostics and prognostics.

1.2.5 IVHM Architectures and Databases

This project element focuses on research for the design and operation of the information, communications, and control infrastructure required to accomplish on-board health management functions on aircraft, including communications with off-board elements such as maintenance information systems. In addition, this element addresses the need for aircraft health management information collection, archival, and dissemination across the industry. Finally, this research element addresses the need for established standards, practices, and protocols applicable to aircraft health management. There are three key areas in this element: 1) research in system design, analysis, and optimization for synthesizing robust IVHM architectures, particularly focusing on the development of methods for early-design phase modeling, decision-making under uncertainty for trade studies, and system analysis and optimization for architecture synthesis; 2) development of an infrastructure to enable information management, data flow, and communications, focusing on the software interface design and requirements for developing infrastructures for data management, development and management of an industry-wide IVHM database, development of communications devices and technologies, and the design and implementation of remote and virtual sensors; and 3) development and validation of architectures, focusing on theoretical underpinnings of distributed adaptive IVHM architectures, particularly those that focus on modularizing high-level system health criteria into subsystem level ones.

The complexity of the health management systems required by next generation aircraft is beyond anything that has been achieved to date. Thus, we need to address a number of key architectural challenges at a fundamental level:

- Effective design methods and system engineering practices are needed to ensure that the IVHM capability is not designed as an afterthought, but rather as a critical subsystem of its own, just as the propulsion and power subsystems, as well as a subsystem that interacts with the remaining critical subsystems.
- Methods and technologies are needed to design an interface and architecture that would be suitable for a variety of computationally efficient IVHM algorithms, including real-time sensor fusion, fault detection, and fault isolation algorithms, data mining algorithms, and physics-based life estimation algorithms, in order to enable all of these algorithms to be easily tested using the same database of historical data.
- Accurate health and status estimation requires pervasive sensing. Providing power and data connectivity to a large number of sensors is a significant design as well as operations and maintenance challenge. New communications and networking technologies need to be

developed to reduce the complexity of instrumentation while providing comprehensive sensory coverage.
- Systems health management is largely focused on the health of independent subsystems. Integration of mission and health information across subsystems that comprise a vehicle remains an elusive goal. Modeling subtle interactions between subsystems is a significant hurdle toward true IVHM. Development of efficient and effective IVHM architectures is another challenge.

The unique contribution of the IVHM Architectures and Databases element is to look at the IVHM capability as a part of the entire system, treating the capability as a system engineering discipline. This has never been done successfully and requires fundamental research in system design and analysis methods.

1.2.5.1 System Design, Analysis, and Optimization of IVHM Architectures

We plan to model the functional architecture of the aircraft in the early design stages using functional models, where the inputs and outputs, the flow of the signals through the system to accomplish required functionality, and the connections and interactions between various functions are determined. Additional functionality and potential failure points and risk elements are discovered through the functional modeling based analysis, risks are assessed and minimized using a portfolio based minimization approach, and the overall system and the IVHM aspects are analyzed and optimized together using system level and subsystem level objectives. Decision support systems and rapid trade analysis tools need to be developed to enable the designers and the analysts/discipline specialists to work together, rather than as separate entities.

These methods and tools will be developed and tested in conjunction with a general-purpose distributed architecture. This effort will focus on the Scalable Processor-Independent Design for Enhanced Reliability (SPIDER), currently under development at LaRC. The purpose of this effort is to design a flexible architecture that can be configured to satisfy a wide range of performance and reliability requirements, while preserving a consistent interface to application programs.

Finally, we will study existing protocols and standards for IVHM data collection, distribution, and archival. These include specific health management standards such as AI-ESTATE and OSA-CBM as well as generic communication protocols used for on-board and off-board health management functions such as IEEE 1553, IEEE 1394, Fiber Channel, and others. We will also work on establishing standards in maturing technology areas such as diagnostic models, models and metadata for sensor fusion, prognostics, and metadata and ontologies for archival of IVHM data.

1.2.5.2 Information Management, Data Flow, and Communications

NASA's Exploration Systems Mission Directorate recently funded two efforts to build IVHM architectures for spacecraft: 1) The ISHM Testbeds and Prototypes Data Services architecture, led by NASA, and 2) the Open System Architecture for ISHM, led by Northrop Grumman. We plan to build upon the two efforts listed above to develop a software architecture for ground-based testing of IVHM algorithms for aircraft. Our architecture will include a database of historical data, a user interface for retrieving this data, and a systems-level interface for feeding this data to algorithms. We plan to develop a database that will provide access to a variety of health management data. Such data may include failure statistics, fault modes and effects, diagnostic models, prognostic and life estimation models, and even raw data sets for purposes of fault detection, isolation, and recovery research. The IVHM database will also allow for seamless integration with a variety of IVHM algorithms, including data mining, machine learning, and exploratory data analysis tools, in order to enable algorithm development and knowledge discovery using the same database of historical data. The IVHM database will be owned and operated by NASA and will be provided as a service to the aircraft industry, U.S. government, and the

R&D community. The database will provide industry-standard access controls to protect proprietary data rights as well as to ensure compliance with ITAR and EAR restrictions.

As part of this research, we will also study and develop methods for wireless power and data transmission technologies for remote sensors. Radio frequency identification (RFID) is an example of a technology that transmits power to a remote, thin-film package with embedded electronics. It is a goal of this work to join together virtual and physical sensors to provide a health monitoring network which can be distributed throughout and embedded within the vehicle structure and its component parts. The network architecture is envisioned as a community of virtual and physical sensors, with no centralized controlling computer. Finally, to the extent that IVHM is the main driver for improving the state-of-the-art in wireless communications, we will seek to develop new communication components and systems necessary to achieve a complete IVHM system.

1.2.5.3 Architecture Development and Validation

In this research element, we will study IVHM architectures using computer-based models and hardware-in-the-loop testbeds. We will also develop and demonstrate a distributed and adaptive health and mission management architecture that provides high resiliency, covers both nominal and off-nominal operations, and increases flexibility in response to changing mission characteristics. In particular this approach:

- Provides locally computable health criteria to system subcomponents
- Ensures that subsystem responses to sudden changes do not cause deleterious effects in full system health.
- Allows the system to rapidly adapt to sudden changes in environment.
- Reconfigures the system in response to malfunctioning (or failing) components.

We plan a distributed and adaptive health and mission management architecture. This new IVHM concept provides high resiliency, covers both nominal and off-nominal operations, and increases flexibility in response to changing mission characteristics. The primary benefit of this approach is in removing the reliance on the existence of precise models or large amounts of data to assess system health. It is particularly well suited to environments where a-priori, in-situ data collection is not possible, which is often the case with unique aerospace systems.

The approach is based on automatically decomposing the full-system health criteria into subsystem health criteria. The health criteria for each subsystem are based on impact on other subsystems as well as the overall system. As a consequence, when subsystems independently take actions to satisfy their own health criteria, these actions also satisfy the overall systems health criteria. This method eliminates the need for costly and inevitably incomplete models of subsystem interactions that lead to unexpected and potentially catastrophic failures. Instead, a distributed IVHM architecture not only improves nominal operations capabilities by ensuring that slow changes in subsystems do not destabilize the overall system, but also off-nominal operations (e.g., propulsion system degradation or failure) by quickly and autonomously responding to new conditions.

1.2.6 Verification, Validation, and Predictive Capability

Successful infusion of vehicle health management technologies into practice necessitates verification and validation of highly complex and integrated systems that employ advanced technologies in areas such as sensors, artificial intelligence, data fusion, diagnostics, and prognostics. The use of these technologies for detecting critical faults in propulsion, flight, and airframe systems is without precedent in civil aviation, and will require a high level of confidence that the diagnosis and predictions made by onboard health management systems are correct and reliable. Furthermore, because of the large number of parameters and complex sub-system interactions inherent in health management systems, verification and validation will be exceptionally difficult using current approaches. IVHM technologies cannot be validated in flight under critical failure conditions. Therefore, verification and validation methods for IVHM systems and technologies must include a predictive capability that enables performance in the application domain in which the system will operate to be inferred from the validation domain assessment. New tools and methods are necessary to build trust in IVHM systems, and to ensure their performance in a flight environment. Moreover, advancement in verification, validation, and predictive capability tools and methods is necessary to achieve the required level of confidence in the systems and technologies that will be developed under the IVHM System Technologies critical focus area.

The objective of this research focus is to develop processes and underlying methods and tools that provide a comprehensive approach to verification and validation (V&V) that will ensure the safe and reliable application of IVHM technologies to civil aviation. The resulting methods and tools will be made publicly available to assist the aerospace community in demonstrating compliance with safety regulations. Research challenges for V&V of IVHM systems include: 1) verifying that the observables of a physical system are sufficient to identify defined classes of faults; 2) verifying and validating detection, diagnosis, and prognosis accuracy for highly non-linear and non-Gaussian failure phenomena; 3) certifying systems that reduce or eliminate the human operator role as the integrator for identifying, diagnosing, and mitigating unplanned events; 4) verifying and validating software-driven diagnosis; 5) establishing, verifying, and validating ultra-reliable communication architectures for flight critical diagnostics; 6) assuring high-confidence avionics and distributed real-time operating systems that support dynamic resource management; and 7) establishing rigorous specifications of the correct behavior of a diagnostic system.

The vision for IVHM V&V is a fully integrated approach to analysis, simulation, and experimental testing. In this vision, analytical methods would be used for software verification and for identifying regions of marginal performance in the large complex state space in which the IVHM system would be operating. Analysis results would be integrated with simulation-based methods for more detailed assessment using guided Monte Carlo techniques. Simulation studies would automatically generate test matrices for real-time simulations, experimental testing, and flight testing. We expect that research results in the next five years will advance the state-of-the-art in the areas of analytical methods, simulation methods, and experimental methods by building upon past advances in formal methods (e.g., model checking, theorem proving, static analysis, runtime monitoring, etc.), software safety engineering, nonlinear dynamic hybrid system analysis, and high-fidelity testing.

It is anticipated that research on analytical and simulation-based methods will be performed in collaboration with NRA awardees and SBIR partners. We also expect to heavily leverage investment by other government agencies, such as the Department of Defense and National Science Foundation, in formal verification methods and other analytical methods. Activities conducted under this element will be coordinated with the V&V requirements of the various IVHM disciplines, and the resulting tools, methods, and techniques developed in response to those requirements will be delivered back to the disciplines. Unique NASA contributions to the Verification, Validation, and Predictive Capability element include: 1) substantial experience in developing advanced formal verification methods for fault-tolerant hardware and software; 2) substantial knowledge of existing software system safety practices, engineering practices and tools, and aviation industry certification and safety standards, regulations, and policy; 3) substantial domain expertise in experimental validation techniques and avionics systems fault detection, mitigation, and recovery; and 4) unique state-of-the-art facilities for conducting closed-loop HIRF effects on avionics, in-flight subscale testing, and airframe structural testing.

1.2.6.1 Analytical Methods

The traditional way of verifying software systems is through human inspection of the software, simulation, and testing. Current approaches provide no guarantee about the quality of the software system because human inspection of software is limited by the abilities of the reviewers, and because simulation and testing explores only a miniscule fraction of the state space of a moderately complex software system. We therefore plan to focus development of analytical methods on establishing a theoretical and scientific basis for: (1) design verification of high confidence IVHM software systems, and the development of tools and methods for building such systems, and (2) evaluating IVHM system performance in a large complex state space.

Mathematically rigorous techniques and tools for the specification, design, and verification of IVHM software systems are needed, and will include advancements in model checking, theorem proving, static analysis, and runtime monitoring. Advances are also needed for the safe use of neural networks so that advanced data-driven diagnostic modeling techniques may be incorporated in diagnosis and prognosis methods. In civil aviation, DO-178B "Software Considerations in Airborne Systems and Equipment Certification" provides the accepted guidance for certifying all new software. New V&V and safety assessment guidelines will be needed for envisioned IVHM software development techniques that are not currently permitted under DO-178B. These new guidelines will be based, in part, on the analysis of safety-case approaches for the assurance of software intensive systems and on the development of specific safety cases for relevant IVHM systems. During the first 5 years of this project, compositional verification techniques for complex and modular IVHM models will be developed. This development will be performed in conjunction with the High Confidence Software Systems coordinating group. Analytical capabilities for formal analysis of ultra-reliable distributed protocols in the presence of multiple failure modes will also be developed. Advances in formal verification methods developed under SBIR funding of NASA, the Air Force Research Laboratory, and the National Science Foundation will be tracked and leveraged.

Robustness analysis for nonlinear adaptive hybrid systems could play an important role in validating the performance of IVHM technologies and systems. Failure detection schemes can experience performance difficulties (such as false positives and false negatives) due to uncertainties associated with modeling errors and noisy measurements. Advances are needed in both deterministic and stochastic robustness analysis methods. Robustness analysis can also identify worst-case combinations of uncertainties, faults and failures for use in guided Monte Carlo simulation and/or experimental studies. In addition, a better understanding of hazard effects on system performance must be developed. In particular, analytical methods to model and assess the threat that electromagnetic and ionizing radiation disturbances pose to underlying IVHM digital systems and wireless components must be addressed. Finally, a clear understanding of what it means for a diagnosis system to be considered safe is paramount. New reliability assessment techniques are needed to establish rigorous specifications for what constitutes fault coverage and correct behavior of a diagnostic system. During the first five years of the project, accomplishments in this area will be made primarily through NRA and SBIR partnerships, and through collaborations with the Integrated Resilient Aircraft Control project.

1.2.6.2 Simulation Methods

Although analysis methods provide insight into robustness issues, and are extremely valuable in predicting problematic regions of operation, simulation-based evaluations are often needed to more thoroughly investigate problematic regions in the state space and assess worst-case combinations of effects. Methods and tools that are needed for application to IVHM technologies and systems include 1) simulation-based robustness analysis tools (such as guided Monte Carlo methods) with automatic test case generation, and 2) real-time simulations that integrate models and data bases for flight dynamics, the propulsion system, and the airframe structure. During the first five years of this project, accomplishments in this area will be made through NRA and SBIR partnerships. In addition, methods and tools currently in development under Phase 2 SBIR funding will be surveyed and assessed for applicability to IVHM technologies. Selected tools will then be adapted and applied to IVHM technology.

1.2.6.3 Experimental Methods

Extensive testing of new IVHM technologies and systems will be necessary not only for demonstrating their benefits to aviation safety, but to also provide a level of assurance that the new technologies and systems are themselves constructed in a safe manner. Experimental validation methods are needed that can encompass medium to large-scale integration of aircraft systems and sub-systems. The envisioned large-scale integration capability for experimental validation will utilize a "Virtual" inter-center Hardware-In-the-Loop (HWIL) laboratory concept whereby key NASA research facilities will be integrated for multi-site, closed-loop testing. During the first five years, testbeds and experimental methods for the following integrated validation experiments will be developed.

(a) Closed-Loop HIRF Effects on Avionics: Closed-loop validation experiments will be performed on the Distributed Flight Control System (DFCS) that was developed by Honeywell under AvSP I. A unique feature of the DFCS is the ability to self-recover from electrical disturbances caused by lightning and HIRF. The DFCS has two LRUs, and each LRU is an Integrated Modular Architecture with partitioned flight control software. Each LRU has dual lock-step processing pairs. Each processing pair is bit synchronized and executes the same control software. At each data frame, a bit-wise comparison of the calculations from the processors is made. If the calculations are identical, state variables are stored in a protected memory. If the calculations from the processors are not identical, the state variables from the last data frame are reloaded to effect a rollback recovery. The two LRUs are networked and interfaced through Remote Interface Units that also have fault handling functions and can initiate recovery in any of the four processing channels. During the HIRF experiments, the DFCS will operate in closed-loop with a flight simulation in order to exercise the flight control function. Experimental methods will be developed to quantifiably validate the self-recovery and fault handling properties of the DFCS.

(b) Airframe-Control System Integration: Structural failure due to crack propagation and/or design limit exceedance has been cited as a causal factor in several accidents. A ground-based, closed-loop testbed capability will be developed that integrates flight simulations, flight profile dynamics loading models, and airframe structures testing facilities. This testbed will provide for the assessment of airframe health management and damage mitigation concepts within a realistic operational environment that will include the capability to impose adverse flight conditions such as atmospheric turbulence. Integration methods will be developed and may be achieved by means of a simplified load/displacement mapping for an element-size test specimen (possibly a simple stiffened or unstiffened panel with an initial flaw) subjected to induced loads (using a servo-hydraulic test frame) as a function of flight simulator outputs. As the damage begins to propagate, the diagnosis and prognosis algorithms (from the IVHM project), will be integrated with mitigation and control techniques (from the IRAC project) and exercised. If additional complexity is desired, two such panels could be considered and assumed to represent different parts of the airframe such that decreasing the loading in one panel would result in an increased loading in the other, thus, requiring a multi-parameter control solution. This relatively simplistic configuration will provide an effective test bed for validating new sensors, damage diagnosis and prognosis algorithms, and mitigation techniques, in addition to providing in-flight input for the control system. More complex configurations can be considered over time.

(c) In-flight Subscale Testing: The Airborne Subscale Transport Aircraft Research (AirSTAR) testbed provides a unique platform for validation of in-flight structural health assessment technologies that cannot be safely flight validated with full-scale vehicles. Modifications necessary to support structural health assessment include the installation of dynamically scaled modular airframe components, such as the empennage, which can be seeded with certain faults, as well as the installation of representative onboard sensors necessary for degradation assessment. For IVHM, the AirSTAR vehicle will serve as one of the target experimental platforms for verifying and validating damage assessment concepts and damage mitigation control strategies, and as such will be part of an "analysis-to-sim-to-flight" V&V capability. For example, analysis and simulation would provide the theoretical basis for ground-based integrated experiments as described in (b), which in turn would provide the proof-of-concept necessary for in-flight testing using the AirSTAR subscale flight platform. During the first five years of the project, IVHM research requirements and components for the AirSTAR testbed will be developed and documented.

1.2.7 System Integration and Assessment

Integration does not happen accidentally. We need to proactively advocate and plan for evolutionary emergence of the envisioned vehicle-wide IVHM capability. The goal of enabling informed decision-making regarding the benefits of IVHM technologies with respect to aerospace system safety, performance, and cost requires an effective approach for quantifying benefits in a meaningful and trustworthy manner. The objective of this work element is to ensure that the Agency progresses toward establishing a sustainable capability to demonstrate and assess a continuously evolving portfolio of IVHM technologies. In particular, this element focuses on (1) integration and demonstration of prototype IVHM capabilities, and (2) quantifiable assessment of the integrated component technologies in terms of performance, safety benefit, and aggregated cost. We will seek approaches that enable us to integrate multiple combinations of IVHM components at various stages of technical maturity and to define and derive metrics for performance, safety, and aggregated cost.

Conceptually, an IVHM system can be thought of as a set of interconnected functional *devices*. A device might be a transducer or instrument, a diagnostic system, or a prognostic system. For the purposes of our research project, a device can be real or simulated, might process observations or models, and could be located on the aircraft or somewhere else. Each device consumes information from connected lower level devices and provides information to one or more higher level devices. Reverse flow of information and wireless communication channels will be present at times. The interface standards and layers of protocols through which these devices communicate are critical components of *integration architecture*.

In order to do meaningful *assessments* for each device, we have to track information related to failure modes and effects, accuracy, reliability, availability, and maintainability. These parameters drive the derivation of safety, cost, and performance metrics. An integration experiment is conducted by assembling a set of devices, allowing information to flow amongst the devices, and then treating that assemblage as a device with its own set of metrics.

To meet the challenges involved with integrating and assessing IVHM technologies, this work element uses a two pronged approach. First, we create a *Master IVHM Integration and Test Plan* that keeps track of significant IVHM test and demonstration activities. This planning and coordination effort is an important mechanism for understanding, demonstrating, and communicating the overall state and direction of the project. The second prong establishes an *Integration Architecture and Assessment Strategy Working Group* to determine strategy and assessment needs and requirements, steer the generation of assessment metrics, support the actual implementation of the integrated tests, and to support the core management team in development of the validated technology portfolio. The formation of special interest technical working groups, comprised of representatives from all four Centers, represents a necessary cross-cutting and comprehensive view into systems integration and assessment. More on the technical working groups can be found in the Management Approach, Section 2.2.5. Together, these efforts result in manageable and flexible integration architecture for actually demonstrating integrated capabilities while automating to the extent practical the generation of metrics for technology assessment. These activities are discussed in more detail below.

1.2.7.1 Master Test and Integration Plan

IVHM is a complicated multidisciplinary technology development effort, and a holistic approach to coordinating the integration of disparate components is required. We will actively look for opportunities to integrate pieces of IVHM and in this plan we will (1) define and document objectives and the requirements for a testbed that integrates simulation and experimental validation capabilities across the IVHM technology focus areas; (2) document benchmark scenarios for integrated validation; (3) plan the milestone demonstrations, including (4) summarizing the history of test results and assessments to date, and (5) summarizing the goals and objectives of planned activities as they relate to overall project objectives. The Master Test and Integration Plan is a living document that will be used to communicate the overall state and direction of the project.

In addition to its focus on integrating IVHM technologies, the Master Test and Integration Plan is also a logical place to formally track cross-project synergies. For example, a gas path sensor being developed under the Integrated Resilient Aircraft Control project could be tested with IVHM systems, saving money and providing added benefits to both projects. The Master Test and Integration Plan will (6) discuss and leverage these cross-project synergies as they relate to IVHM objectives. Finally, it is important to recognize that the portfolio of capability demonstrations reflected in this document will be the result of implementing integration architecture and an assessment strategy. Thus, the Master Test and Integration Plan (7) provides traceability to requirements and directly contributes to construction of quantified project metrics. This task will thus leverage the team's rich legacy in test planning, systems engineering, and analysis to ensure that IVHM investment results in demonstrable progress toward the ultimate (level 4) goal.

1.2.7.2 Integration Architecture and Assessment Strategy Working Group

IVHM will establish a four-center working group to coordinate system integration architecture and strategy. Specifically, this group will:

1. Conduct needs assessment/goals analysis for the IVHM technology user base
2. Conduct IVHM technology gaps analysis
3. Define requirements and scenarios for an integrated IVHM testbed
4. Establish planning inputs and priorities for integration and test planning
5. Establish collaborative system development and demonstration testbed access requirements
6. Collaborate with other project elements to conduct integrated component demonstrations
7. Conduct assessment of the effectiveness of demonstrated technologies
8. Document operational, technical standards, and systems-oriented architectural views of IVHM R&D environments
9. Establish IVHM assessment metrics for performance, and safety and cost benefit
10. Implement and maintain assessment support tools for IVHM Project.

In order for IVHM systems to be developed and accepted, they must be validated in a realistic environment that requires some sort of demonstration "facility" be it a test vehicle, a hardware-in-the-loop lab facility or a simulation environment. The team members maintain a number of existing facilities, and other facilities/testbeds exist outside NASA. As IVHM research progresses, the need for combined systems level testing in a standardized manner increases. The combination of integration architecture, assessment strategy, and top-level test planning are important components of a sustainable technology development effort. The expected outcome is a virtual integration facility addressing the need for standardized but flexible integration architecture. The ability to build and test components throughout the development cycle in an integrated fashion is in some ways a metaphor for the actual IVHM systems that ultimately get built.

Integration architecture that governs the actual integration is tightly coupled to the discipline of systems engineering, and a key to successful and scalable integration involves standardization on transport protocols (networks & busses) followed by standardization of the content that flows over those conduits. Regarding the content, there are basically two schools of thought. The dominant school treats the “enterprise” as a complicated but predictable "system of systems," or a mega-system dominated by processes. The emergent school sees the enterprise as a "complex adaptive system” dominated by cognitive rules, with interesting, unpredictable, and sometimes undesirable behavior when the components start interacting in nonlinear fashion. The documentation of integration architecture can be formidable but is manageable for our project. Guidelines for defining architecture are provided by the DOD Architecture Framework (DODAF) and by the Federal Enterprise Architecture Framework (FEAF). As a civilian agency, NASA architects generally advocate conformance to FEAF, but systems integration projects like IVHM are much easier to align with the DODAF framework. Our integration architecture documentation suite will be based on the DOD Architecture Framework and shall cover operational, systems, and technical views of IVHM systems integration. All systems integration and assessment requirements will be recorded as part of the architecture documentation.

Assessment of integrated technologies is accomplished first with an integration architecture and assessment strategy feeding a test and integration plan. The resulting capability demonstrations, conducted as needed by team members that potentially span all work elements, are then reviewed by the assessment team. The assessment report becomes part of the project database while lessons learned feed back into the assessment strategy itself in order to influence future test and demonstration activity. Integration architecture, assessment strategy, and assessments are all referenceable document entities needed to validate a technology portfolio. Thus, documents produced under this work element are maintained as part of the project database.

The schedule of deliverables and milestones under this work element target a baseline set of documents, followed by semiannual updates and punctuated by biennial integrated demonstrations of capabilities. Numerous component tests and smaller integrated demonstrations are anticipated throughout the project life cycle, and will be appropriately tracked by the core management team at the next level of detail.

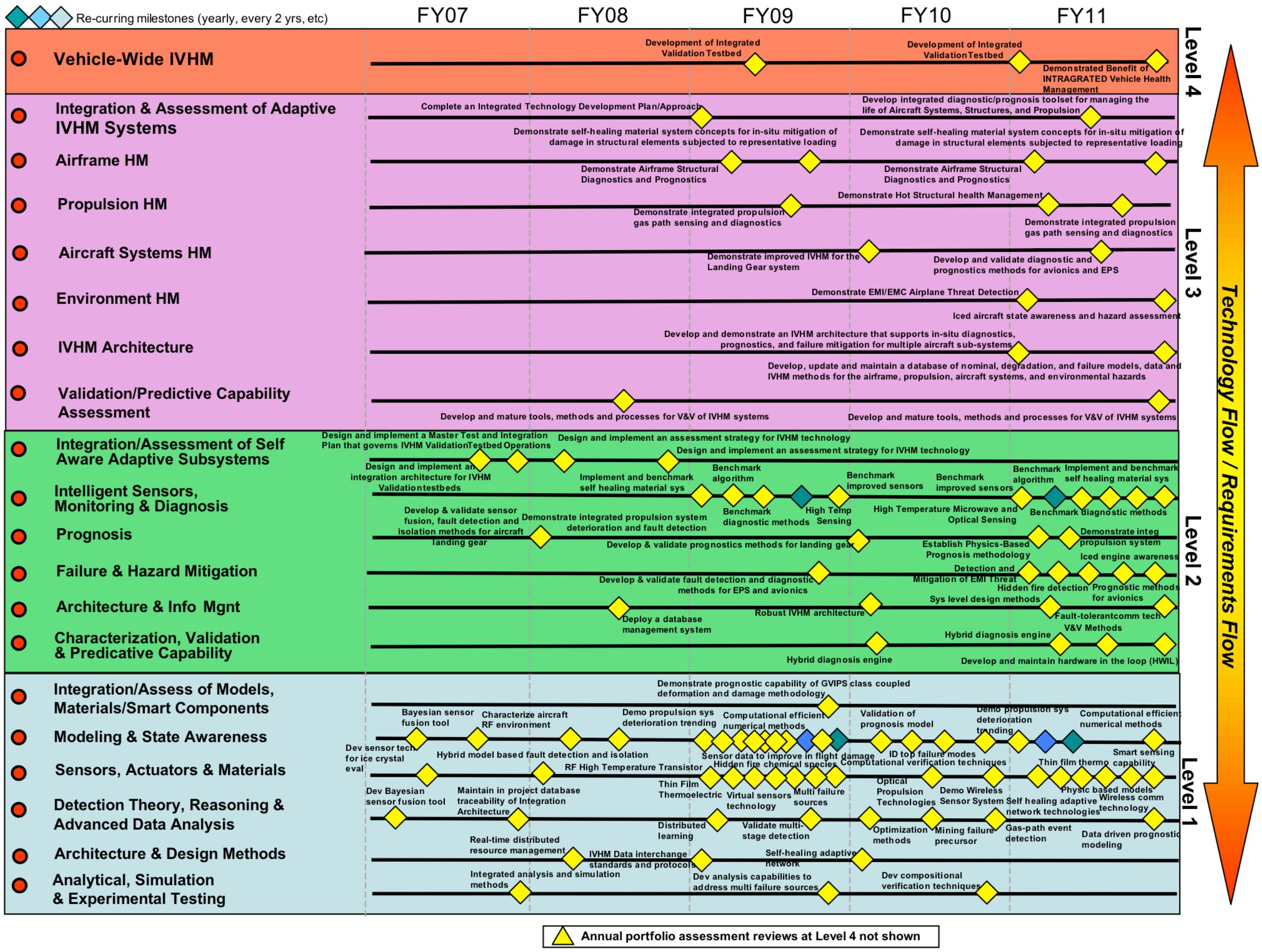

Figure 2: IVHM 5-year Milestone Roadmap

1.3 Milestones and Metrics

The development of IVHM technologies represents a broad area of opportunity, as the benefits are widely recognized through the Government and industry, yet the current state-of-the-art is immature. The goal of the NASA effort in IVHM is to develop multidisciplinary vehicle-wide health management systems, tools, and technologies for 1) graceful recovery from in-flight failures, 2) prevention and adaptation for in-flight operability, and 3) informed logistics and maintenance. Table 2 milestones were focused from the 10-year roadmap based on 1) criticality and fundamental applicability of the work, 2) industry responses to the RFI, and 3) available NASA workforce. The milestones are documented with metrics as well as exit criteria, and are structured so that progress can be easily measured and evaluated.

The IVHM roadmap with a five-year outlook is shown in Figure 3. For the purposes of this technical plan summary, we are limiting the presentation of milestones in this section to the major accomplishments planned in the first five years of the project.

Table 2: IVHM Project Milestones

Level 4 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
4.1	Development of IVHM Databases and Integrated Validation Testbed	2009, 2011	3.1.1, 3.6.1
i) Document capability of IVHM testbed that integrates simulation and experimental validation for structures, propulsion, aircraft systems health management technologies, and at least one environmental hazard management technology. (2009) ii) Document Contents and Features of IVHM Technology Database (2011)			
4.2	Demonstrated Benefit of **INTEGRATED** Vehicle Health Management and Environmental Hazard Management Technologies	2011	3.1.2, 3.2.1, 3.3.1, 3.4.1, 3.5.1, 3.5.2
i) Perform experiments that integrate two or more HM technologies (i.e. Airframe, Propulsion, Aircraft Systems, Architectures models, sensor data, and/or diagnostic algorithms) and at least one environmental hazard management technology. ii) Quantify and document the benefit of integrated vs. decoupled diagnostics for benchmark scenarios.			

Level 3 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
3.1.1	Develop integrated diagnostic/prognosis toolset for managing the life of Aircraft Systems, Structure, and Propulsion	2011	2.1.1, 2.1.2, 2.1.3
Initial Demonstration of minimal set of Integrated Validation diagnostic/prognostic tools by 4Qtr FY07, with major demonstrations at least every two years (FY2009; FY2011). Quantifiable metrics are 1) The number of tests and demonstrations conducted as part of Integrated Testbed development; 2) the number of assessment reports derived from tests or other sources; 3) and the number of technologies entered into project database.			
3.1.2	Complete an Integrated Technology Development Plan / Approach	2009	2.1.1, 2.1.2, 2.1.3
Release document package on regular schedule. Initial draft by 3rd Qtr FY07, baseline document set released Sep07. Updates released at 6-month intervals. This deliverable is a documentation suite within project database.			
3.2.1	Demonstrate Airframe Structural Diagnostics and Prognostics	2011	2.2.1, 2.2.2, 2.2.3
i) Demonstrate application of integrated diagnostic/prognostic algorithms incorporating new sensors, inverse methods, and computationally efficient predictive methods and benchmarked on a **metallic** Airframe structural component subjected to mechanical loads, with predictions of displacements, strains, and stresses to within 5% and predictions of failure quantities to within 10% of tested values; or, ii) Demonstrate application of integrated diagnostic/prognostic algorithms incorporating new sensors, inverse methods, and computationally efficient predictive methods and benchmarked on a **composite**			

Level 3 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
Airframe structural component subjected to mechanical loads, with predictions of displacements, strains, and stresses to within 10% and predictions of failure quantities to within 15% of tested values.			
3.2.2	Demonstrate self-healing material system concepts for in-situ mitigation of damage in structural elements subjected to representative loading	2011	2.2.4
i) Demonstrate an increase in critical flaw size by at least a factor of two for a **metallic** Airframe structural component subjected to mechanical loads; or, ii) Demonstrate residual compression after impact strength of at least 60% of the undamaged compressive strength in a **composite** Airframe structural component impacted at energies corresponding to catastrophic failure in brittle epoxy composite material systems.			
3.3.1	Demonstrate integrated propulsion gas path sensing and diagnostics	2009, 2011	2.3.1, 2.3.2, 2.3.3
i) In simulation, quantify the improved trending accuracy provided by the advanced propulsion HM sensors under NASA development. Demonstrate 10% improvement in estimation accuracy. (2009) ii) Conduct simulation demonstration of advanced propulsion gas path health management system (includes enhanced algorithms and advanced sensors). Demonstrate 10% improvement in diagnostic accuracy with advanced sensors. (2011)			
3.3.2	Demonstrate Hot Structural Health Management	2011	2.3.2, 2.3.3, 2.3.4
Demonstrate a 15% enlargement in predictive horizon window for static structures at elevated (+500^{o}C) temperature given complex load history involving overloads.			
3.4.1	Demonstrate improved IVHM for the Landing Gear system	2010	2.4.1, 2.4.2
i) Demonstrate integrated diagnostics for Landing Gear components and sub-systems in the ALDF testbed with diagnostic coverage of seeded/seedable faults and with no more than 10% false negative and 10% false positive rates; ii) Demonstrate prognostic capability with 90% accuracy for selected landing gear components using existing historical data.			
3.4.2	Develop and validate IVHM diagnostic and prognostics methods for Avionics and EPS	2011	2.4.3, 2.4.4
i) Demonstrate diagnostic coverage of seeded/seedable faults in ADAPT testbed with no more than 10% false negative and 10% false positive rates; prognostic coverage of 5 life-limited EPS components. ii) Demonstrate a diagnostic and prognostic system for Avionics using SAFETI Lab testbed that can detect faults, malfunctions, and failures with no more than 10% false alarm rate, and predict impending failures with 90% accuracy.			
3.5.1	Iced aircraft state awareness and hazard assessment	2011	2.5.1
Monitor aircraft state during icing encounters, identify and assess aerodynamic performance, including rate of change, and inform crew through hazard assessment algorithm of 10% precautionary action and 15% mandatory action for degraded aircraft performance.			

<table>
<tr><td colspan="4">Level 3 Milestones</td></tr>
<tr><td>Number</td><td>Title</td><td>Year</td><td>Dependencies</td></tr>
<tr><td colspan="4">Exit Criteria / Metrics</td></tr>
<tr><td>3.5.2</td><td>Demonstrate EMI/EMC Airplane Threat Detection</td><td>2011</td><td>2.5.2</td></tr>
<tr><td colspan="4">i) Develop methodologies to predict, detect and mitigate EMI/EMC hazards from lightning, HIRF, portable electronic devices, pulsed and burst type emitters, UWB, and other emerging technologies for aerospace vehicles; or
ii) Demonstrate an airplane RF environment threat detection system able to respond to hazards in the navigation, communication and wireless sensor bands.</td></tr>
<tr><td>3.6.1</td><td>Develop, update, and maintain a database of nominal, degradation, and failure models, data and IVHM methods for the airframe, propulsion, aircraft systems, and environmental hazards</td><td>2011</td><td>2.6.1</td></tr>
<tr><td colspan="4">Document contents and features of IVHM database, and assess the performance of plug-in data analysis tools available for use with the database.</td></tr>
<tr><td>3.6.2</td><td>Develop and demonstrate an IVHM architecture that supports in-situ diagnostics, prognostics, and failure mitigation for multiple aircraft sub-systems</td><td>2011</td><td>2.6.2, 2.6.3, 2.6.4</td></tr>
<tr><td colspan="4">Provide theorical proof and empirical evidence that a multi-system IVHM architecture testbed is tolerant to any two independent points of failure in the sensing, communications, or processing network.</td></tr>
<tr><td>3.7.1</td><td>Develop and mature tools, methods, and processes for V&V of IVHM systems</td><td>2008, 2011</td><td>2.7.1, 2.7.2, 2.7.3, 2.7.4</td></tr>
<tr><td colspan="4">Demonstrate and document application of integrated V&V Tools (such as those currently being developed under Phase 2 SBIR funding) for IVHM technology V&V. (2011)
i) Verify through exhaustive Monte Carlo simulation that analytical methods identify 100% of worst case performance conditions for selected FDI system. (2009)
ii) Verify that guided simulation methods based on analysis automatically generate 100% of the worst case performance conditions identified in (i) for use in experimental testing of selected FDI system. (2011)</td></tr>
</table>

Level 2 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
2.1.1	Design and implement an integration architecture for IVHM Validation testbed	2007	1.1.1
Quantifiable metric #1 is a rollup of percentage of TBD functional needs met by implemented components of the architecture. First estimate of this metric delivered by Oct 2007, with semiannual updates commensurate with reporting schedule. Target is monotonically increasing metric. - Define requirements for testbed that integrates simulation and experimental validation capability for structures, propulsion, aircraft systems health management (HM) technologies, and at least one environmental hazard management technology. (2007) - Define benchmark scenarios for integrated validation of structures, propulsion, aircraft systems health management technologies, and at least one environmental hazard management technology. (2008)			
2.1.2	Design and implement an assessment strategy for IVHM technology	2008	1.1.1
For each category of safety, cost, and performance, the number of assessment methods applicable across multiple IVHM elements must be tracked. A quantifiable metric is the number of methods weighted by the number of elements served by the method.			
2.1.3	Design and implement a Master Test and Integration Plan that governs IVHM Validation Testbed Operations	2007	2.1.1
Quantifiable metrics include number of tests, experiments, or demonstrations planned and percentage of planned activities completed.			
2.2.1	Implement and benchmark improved sensors for detecting damage	2009, 2011	1.2.1, 1.2.2, 1.2.3, 1.2.4
i) Demonstrate an embedded sensory material system that has a probability of detection that is at least a factor of 3 greater than that observed in the benchmark metallic structural alloy; or, ii) Demonstrate a high-density multi-functional fiber-optic based sensor array capable of greater than 10% FSR µstrain on a representative structure under representative loading; or, iii) Demonstrate a MEMS smart sensor capable of greater than 10% FSR µstrain resolution on a representative structure under representative loading; or, iv) Demonstrate a single wall carbon nanotube sensor array for multi-axis strain mapping on a representative structure under representative loading; or, v) Demonstrate electrical impedance detection methods capable of 80% accuracy for multiple failure modes in non-metallic structural materials on a representative structure under representative loading.			
2.2.2	Implement, integrate and benchmark diagnostic methods for selected aircraft components	2009, 2011	1.2.5
i) Demonstrate a 3-core fiber to detect at least 50% of known damage/failure states for a representative structure under representative cyclic loading; or, ii) Demonstrate Fiber Bragg Grating sensors to measure fatigue damage in a representative structure under representative cyclic loading to within 10%; or, iii) Demonstrate inverse structural health methods capable of detecting structural damage with 90% accuracy in a representative structure under representative loading.			
2.2.3	Implement, integrate and benchmark algorithms for prediction of damage	2009, 2011	1.2.6, 1.2.7

Level 2 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
i) Develop the extended finite method for estimating residual life of a representative structure under representative loading; or, ii) Develop an integrated (hybrid sensor-predictive) prognostic methodology capable of 90% accuracy compared to a corresponding benchmark solution for a representative structure under representative loading; or, iii) Develop prognostic system based on electrical impedance damage detection methods integrated with non-deterministic damage models with 80% accuracy for a representative structure under representative loading.			
2.2.4	Implement and benchmark integrated self-healing material systems	Year 2009, 2011	1.2.4, 1.2.8
i) Demonstrate a reduction in equivalent flaw size by at least a factor of 2 in a healing metallic material system compared with the benchmark metallic system for a representative structure under representative loading; or, ii) Demonstrate compression after impact strength of at least 60% of the undamaged compressive strength in a composite material impacted at energies corresponding to catastrophic failure in brittle epoxy composite material systems.			
2.3.1	Demonstrate integrated propulsion system deterioration and fault detection	2009 2011	1.3.1, 1.3.2
i) In Monte Carlo simulation studies identify and document propulsion gas path health management diagnostics scenarios that currently result in >0.001 false alarms per flight, and the fault scenarios that result in >0.5 missed detections per fault occurrence. (2009) ii) Conduct simulation demonstration of advanced propulsion gas path health management system (includes enhance algorithms and advanced sensors) applied to the challenging diagnostic scenarios previously identified. Demonstrate <0.0005 false alarms (per flight) and <0.25 missed detections per fault occurrence. (2011) iii) Demonstrate reliable diagnosis of thrust asymmetry conditions greater than 10% net thrust.			
2.3.2	Demonstrate High Temperature Sensing, Wireless Communication, and Power Scavenging for Propulsion Health Management	2009 2011	1.3.3, 1.3.4, 1.3.5
i) Breadboard demonstration of power scavenging at 300 C with 3V voltage, pressure sensor at 300 C, and a wireless circuit with RF communications at 300 C over 1 m distance. (2009) ii) Demonstrate integrated self powered wireless sensor system at 500 C with data transmission over 1 m distance minimum and operational life of at least 1 hr. (2011)			
2.3.3	High Temperature Microwave and Optical Sensing for Propulsion Health Management	2011	1.3.6
Couple distributed (more than 5) dynamic (>50 Hz) fiber optic sensor data into structural diagnostic / prognostic and gas path propulsion health monitoring models.			
2.3.4	Establish Physics-Based Prognosis methodology for high temperature static structural components	2011	1.3.6, 1.3.7, 1.3.8
Conduct blind comparison of simulation data with corresponding experimentally measured strain fields and failure modes for prognostically challenging static structural problems. Achieve qualitatively			

<table>
<tr><th colspan="4">Level 2 Milestones</th></tr>
<tr><th>Number</th><th>Title</th><th>Year</th><th>Dependencies</th></tr>
<tr><th colspan="4">Exit Criteria / Metrics</th></tr>
<tr><td colspan="4">similar strain field and failure patterns given complex multi-axial load histories, geometric imperfections and/or stress risers with a quantitative accuracy similar to that achievable under idealized conditions (for example monotonic biaxial (5-10%), constant range biaxial cyclic tests (10-30%)).</td></tr>
<tr><td>2.4.1</td><td>Develop and validate sensor fusion, fault detection, and isolation methods for aircraft landing gear</td><td>2008</td><td>1.4.1, 1.4.2</td></tr>
<tr><td colspan="4">Demonstrate diagnostic coverage of seeded/seedable faults in ALDF testbed with no more than 20% false negative and 20% false positive rates.</td></tr>
<tr><td>2.4.2</td><td>Develop and validate prognostic methods for landing gear degradation and failures</td><td>2010</td><td>1.4.3</td></tr>
<tr><td colspan="4">Demonstrate prognostic coverage of selected landing gear components with 90% accuracy.</td></tr>
<tr><td>2.4.3</td><td>Develop and validate fault detection and diagnostic methods for complex EPS and Avionics systems</td><td>2009</td><td>1.4.1, 1.4.2, 1.4.5, 1.4.6</td></tr>
<tr><td colspan="4">i) Demonstrate diagnostic coverage of seeded/seedable faults in ADAPT testbed with no more than 20% false negative and 20% false positive rates.
ii) Demonstrate diagnostic coverage of seeded/seedable faults in SAFETI Lab testbed with no more than 20% false negative and 20% false positive rates.</td></tr>
<tr><td>2.4.4</td><td>Develop and validate prognostic methods for avionics and electronics degradation and failures</td><td>2011</td><td>1.4.6, 1.4.7, 1.4.8</td></tr>
<tr><td colspan="4">i) Demonstrate prognostic coverage of selected components in ADAPT testbed with 90% confidence level.
ii) Demonstrate prognostic coverage of selected components in SAFETI Lab testbed with 90% confidence level.</td></tr>
<tr><td>2.5.1</td><td>Develop Technologies for Iced Engine State Awareness and Hazard Assessment</td><td>2011</td><td>1.5.1, 1.5.2</td></tr>
<tr><td colspan="4">Demonstrate on-board monitoring and sensing capabilities with sufficient time response to alert crews within 3 minutes of an impending ice crystal hazardous encounter.</td></tr>
<tr><td>2.5.2</td><td>Develop Technologies for Detection and Mitigation of EMI Threats</td><td>2011</td><td>1.5.3, 1.5.4</td></tr>
<tr><td colspan="4">i) Evaluate techniques for EM modeling & coupling mitigation in aluminum/composite/etc. fuselages.
ii) Develop EM Shielding, antenna design, and circuit protection devices for detection and mitigation of Lightning, HIRF and unauthorized RF environments.
iii) Coordinate with RTCA, AVSI, FAA and ongoing NASA projects. Security conferences & workshops. Continue SBIR support efforts.</td></tr>
<tr><td>2.5.4</td><td>Develop and Assess Mitigation Concepts for Single Event Effects caused by Ionizing Radiation</td><td>2011</td><td>1.5.8</td></tr>
<tr><td colspan="4">i) Perform and document the design of a simple FCC which uses architectural mitigation strategies in combination with a minimal number of rad-hard components. (2009)
ii) Develop a hardware prototype of the FCC designed for robustness to SEE. Characterize and document operational performance and determine recovery time with microsecond accuracy. (2010)
ii) Perform closed-loop SEE tests of FCC prototype. Demonstrate and quantify transparent recovery function during neutron particle exposure that enables uninterrupted fault tolerant control. (2011)</td></tr>
</table>

Level 2 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
2.6.1	Deploy a database management system that enables capture, analysis and dissemination of diagnostic and prognosis information.	2008	1.6.2
Database made available to non-NASA users for user registration and access; one plug-in data analysis tool available			
2.6.2	Fault-tolerant communications technologies for onboard IVHM data flow	2011	1.6.3, 1.6.4
Use of integrated transceiver and antenna packages at a determined optimum frequency in an assembled fault-tolerant network while maintaining link failure detection time less than 500ms and overall route convergence time less than 1 second.			
2.6.3	System-level design methods and tools to enable robust integration of the subsystems and IVHM	2011	1.6.1, 1.6.5, 1.6.6, 1.6.7
100% coverage of flight critical faults achieved (via testability analysis) with 20% fewer design cycles compared to traditional design methods.			
2.6.4	Develop and demonstrate a robust distributed IVHM architecture	2010	1.6.1, 1.6.3, 1.6.4, 1.6.8
Using a ground testbed that includes at least three subsystems, empirically demonstrate robustness to any single processing node failure.			
2.7.1	Develop and maintain hardware in the loop (HWIL) subsystem testbeds to assess the performance of sensors and algorithms for diagnostics and prognostics	2011	None
i) Demonstrate operation of the AirSTAR testbed in conjunction with the AirSTAR simulation used to emulate subsystem faults and/or failures. Collect and archive sensor data from a statistically significant number of simulated flights and document characterizations of fault/failure conditions and effects. (2007) ii) Demonstrate experimental validation methods for self-recovery performance of a primary flight control computer incorporating a Rapid Recoverable Processor prototype in a closed-loop system utilizing fly-by-wire primary flight controls on an Integrated Modular Avionics (IMA) platform in a redundant configuration. Quantify with microsecond precision the innerloop recovery time from a simulated memory fault in a single channel (2008); Quantify with microsecond precision the innerloop recovery time from a simulated memory fault in two or more channels. (2010) iii) Demonstrate operation of linked lab capability for closed-loop assessment of structural health management technologies. Perform cyclic testing of a structural panel with propagating damage using a dynamic load profile determined from a remote flight simulation operating in closed-loop. Quantify latency of closed-loop data transfer with millisecond accuracy. (2010) iv) Develop and demonstrate HWIL testbed for prognostic and failure mitigation avionics subsystem electronics with standards for integrating directly with subsystem testbeds. Utilize avionics IVHM electronics to predict flight control smart actuator failure and verify that accuracy is within 20% based on historical failure data. (2011) v) Develop and characterize sensor concepts for capturing in-flight load data on the AirSTAR sub-scale vehicle. Collect and archive sensor data collected from a statistically significant number of			

Level 2 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
flights. (2009)			
2.7.2	Measure and characterize the performance of a hybrid diagnosis engine using HWIL testbeds	2010	None
Demonstrate ground-based experimental validation methods for detection & diagnosis of non-propagating damage on AirSTAR testbed component instrumented with sensors for structure health management. Quantify detection and diagnosis performance in terms of diagnosis accuracy (i.e. characterization of damage size and location), detection probability, and false alarm probably.			
2.7.3	Measure and characterize the performance of a hybrid diagnosis engine using flight testing	2011 (2016)	None
i) Define and document requirements for in-flight validation of IVHM technologies using the AirSTAR GTM. (2009) ii) Design and fabricate GTM components that enable instrumentation and characterization of dynamic load profile with quantified accuracy. (2011)			
2.7.4	Develop and demonstrate V & V methods, techniques, and tools for sensor fusion/diagnosis technology and diagnostic inference engines and models	2011	1.7.1, 1.7.2
i) Develop and document tool design concept for Verification and Validation of self-correcting electronics; demonstrate capability on a minimum of two candidate self-correcting designs. (2010) ii) Demonstrate ground-based validation methods involving closed-loop experiments for assessment of structural health management technologies integrated with IRAC-developed structural load alleviation technologies. Conduct experiment using structural panel with IVHM sensors integrated with diagnosis and load alleviation algorithms. Quantify that at least a 10 % load alleviation is achieved. (2011)			

Level 1 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
1.1.1	Maintain in Project Database traceability of Integration Architecture and integrated technology assessments to communication across sub-projects and inter-Center technical working groups	2007, 2009	
Quantifiable metrics include 1) number of functional needs in the IVHM integration architecture with traceability to specific subproject and technical working group inputs; 2) number of assessment reports each technical working group contributes to.			
1.2.1	Develop and demonstrate structural sensors to provide intelligent or smart sensing capabilities	2009, 2011	
i) Develop a high-density multi-functional fiber-optic based sensor array capable of better than 10% FSR µstrain and temperature resolution; or, ii) Develop a MEMS smart sensor capable of better than 10% FSR µstrain resolution; or, iii) Develop a single wall carbon nanotube sensor array for multi-axis strain mapping accurate to within 10%; or, iv) Develop a sensory material with twice the NDE response (using a commercial NDE tool) compared			

Level 1 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
with the corresponding benchmark material; or, v) Develop a fiber rosette strain measurement to within 5% of the benchmark foil strain gage measurements; or, vi) Develop a real-time Bragg Grating demodulation technology to measure the strain of 3-core fiber to with 90% accuracy.			
1.2.2	Develop and demonstrate self-powered sensors for airframe structural health monitoring	2009, 2011	
Develop a wireless micro-power sensor capable of functioning with 100% of required energy from energy harvesting sources.			
1.2.3	Develop and validate physics-based models of sensor performance	2009, 2011	
i) Develop models of fiber optic sensors with sufficient fidelity for SHM applications; or, ii) Develop models of MEMS sensors with sufficient fidelity for SHM applications; or, iii) Develop models of nanoscale sensors with sufficient fidelity for SHM applications			
1.2.4	Develop computational, experimental and processing methods for development of IVHM materials	2009, 2011	
i) Develop molecular dynamics, multiscale and micromechanics methods for predicting damage evolution and propagation in IVHM material systems accurate to within 20% of measured values; or, ii) Develop an in-situ method for testing IVHM material systems within a Scanning Electron Microscope allowing direct measurement of the correspondence between NDE response and crack tip damage mechanisms accurate to within 20% of theoretical values; or, iii) Develop processing methods for development of IVHM materials that improve detection of damage by 50% compared with baseline material or reduce crack driving force by 50% compared with baseline materials; or, iv) Develop processing techniques for OFDR FOSS sensor to improve measurement rate by 100%			
1.2.5	Develop technologies for interpreting deformation and damage data from sensors	2009, 2011	
i) Develop a non-deterministic structural damage detection method with 90% accuracy; or, ii) Develop a technique for modeling electrical impedances based on finite element heat transfer models with 80% accuracy; or, iii) Used IFEM technique on 3-core fiber data to predict shape of test coupon with 90% accuracy			
1.2.6	Develop computationally efficient numerical methods for in-flight prognosis of damage	2009, 2011	
i) Develop extended finite element method for estimating damage growth in metallic structural components; ii) Develop computationally efficient response surface-based methods for estimating damage growth			
1.2.7	Develop methods for integration of sensor data to improve in-flight damage & life prediction capabilities	2009, 2011	
i) Develop computationally efficient prognostic model incorporating diagnostic information with 90% accuracy; or, ii) Develop hybrid state model for fault diagnosis of landing gear to identify 95% of faults tested with simulated input scenarios			

Level 1 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
1.2.8	Develop and demonstrate materials for mitigation of structural damage	2009, 2011	
i) Demonstrate a reduction in crack driving force by at least a factor of 2 compared with baseline structural metallic material; or, ii) Develop scalable processing method for production of self-healing composite matrix materials			
1.3.1	Demonstrate propulsion system deterioration trending and virtual sensing capability	2009	
i) In simulation demonstrate on-board propulsion performance deterioration trending with robust event detection and discrimination capability and < 2% average estimation error. ii) Demonstrate estimation of thrust asymmetry conditions > 10% within 20% accuracy.			
1.3.2	Demonstrate propulsion gas-path event detection capability	2010	
Demonstrate propulsion gas-path event detection techniques under static deterioration levels with <0.0005 false alarms (per flight) and <0.25 missed detections per fault occurrence.			
1.3.3	Thin Film Thermoelectrics	2009, 2011	
i) Demonstrate uni-couple thin film TE at 500°C in oxidizing environment for >10 hours (2009) ii) Demonstrate thin-film TE module producing > 3Vdc at 500°C in oxidizing environment for > 100 hours (2011)			
1.3.4	Demonstrate Wireless Sensor System Elements	2010	
Demonstrate RF sensor data signal transmission operating at 500 C with circuit, including RF transistor, antenna, and sensor, integrated onto a single package.			
1.3.5	RF High Temperature Transistor	2009	
Build and demonstrate RF transistor for use in wireless communication applications that operate at 500 C for greater than 10 hours.			
1.3.6	Optical Propulsion Health Monitoring Fundamental Technologies	2010	
i) Dynamic High temperature (600 C) biaxial fiber optic strain sensor capable of 20 microstrain resolution with 1000 hour lifetime ii) Dynamic Temperature sensor capable of 1000 C operation with less than +/-20 C error with 1000 hour lifetime iii) Wireless optical link from static to rotating components with less than 6 db loss			
1.3.7	Demonstrate prognostic capability of GVIPS class coupled deformation and damage methodology	2009	
Identify appropriate local and global failure criteria. Demonstrate using finite element based model simulations that the methodology can capture the complex interactive effects of load multiaxiality, complex load histories (e.g., overloads, cyclic, thermomechanical, etc.), geometric imperfections and structural stress risers on the deformation and life response with the same level of accuracy (<5%) under idealized uniaxial conditions. Refine/enhance/verify methodology (2009)			

Level 1 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
1.3.8	Establish experimental database for characterization and validation of prognosis model	2010	
Complete prognostically challanging experiments on selected material for use in characterizing and validating deformation and lifing prognosis model. Corresponding signature data (properties, failure modes, response curves) will be loaded into web-based database along with pedigree information for use by research community at large. The number and type of tests to be run will be established and documented within the first year of the program.			
1.4.1	Develop Bayesian sensor fusion tools for robust state estimation	2007	
Demonstrate better than 95% accuracy in state estimation with less than 1 second delay in state tracking using a seeded fault testbed			
1.4.2	Hybrid model-based fault detection and isolation	2008	
Demonstrate diagnostic coverage with no more than 10% false negative and 10% false positive fault isolation rates and ambiguity groups of 2 or less using a seeded fault testbed with discrete, continuous, and transient fault behavior			
1.4.3	Data-driven prognostic and life estimation modeling for selected landing gear components	2009	
Develop prognostic model for a selected landing gear component, and demonstrate 90% accuracy using existing historical data.			
1.4.4	Develop and validate multi-stage detection with decision fusion for Flight Control Computer state estimation and function monitoring	2009	
Demonstrate less than 10% false negative and 10% false positive rates in detecting failure effects due to HIRF			
1.4.5	Develop Bayesian methods for discrimination of EPS sensor failures from true failures	2007	
Demonstrate better than 95% accuracy in discriminating sensor failures from true failures using seeded faults in the ADAPT testbed			
1.4.6	Develop and demonstrate distributed learning and inference for system-wide state estimation	2009	
Demonstrate better than 95% accuracy in isolating system-wide failures with ambiguity groups of 2 or less using seeded faults in the SAFETI Lab testbed			
1.4,7	Data-driven prognostic and life estimation modeling for selected electronic components	2011	
Develop a prognostic life estimation model for a selected electronic component with RUL estimation of more than 3 hours at a 95% confidence level			
1.4.8	Identify top failure modes on EPS components and develop fundamental failure progression physics and mathematical models	2010	
Develop failure progression models for three selected electronic components with 90% or better degradation tracking accuracy at the 90% confidence level			

Level 1 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
1.5.1	Characterization of ice crystal/mixed phase for engine icing	2009, 2010	
i) Generate a database representative of convective storm high ice water content icing conditions and measure the cloud microphysical properties. (2009) ii) Update the 1950's database and analyze ice water content against altitude, temperature, and particle size using more accurate instrumentation, increased altitude and extent, and expanded conditions within the convective storm cells. (2010)			
1.5.2	Develop sensor technology for ice crystal evaluation and demonstrate performance in flight research test	2007, 2008	
i) Install flight research measurement equipment and perform flight readiness checks of ice crystal measuring systems for follow-on flight research campaigns. (2007) ii) Increase accuracy of measured total water content by 50% over the existing instrumentation in high ice water content conditions and assess in-flight. (2008)			
1.5.3	Modeling aircraft RF environment	2009	
Demonstrate predictive capability of RF propagation analysis design to optimize IVHM sensor systems			
1.5.4	Characterize aircraft RF environment	2007, 2008, 2009	
i) NASA Report on avionics system susceptibility to RFID type emissions (FAA IA), Flight EMI effect studies on aeronautical CNS systems, flight RF environment on GA aircraft. (2007) ii) RTCA document describing PED tolerant aircraft design criteria. NASA Report on aircraft RF coupling mitigation techniques. NASA Report and database describing aircraft RF interference path loss measurements (2008) iii) Develop data and analysis tools to facilitate aircraft wireless sensor system design. (2009)			
1.5.8	Characterize Single Event Effects on an Aircraft System and Develop Sensors for Detecting Ionizing Radiation	2011	
i) Develop and validate hybrid mathematical models that predict the performance and effects of roll back recovery strategies using SEE data. Quantify the modeling accuracy. (2007, 2009, 2011) ii) Define and document candidate architectures and fault tolerant paradigms for achieving a minimum 50% improvement in robustness over existing approaches suitable for harsh neutron particle environments. (2008) iii) Develop and utilize sensors for the measurement of ionizing radiation and other environmental factors using Fiber-optic, MEMS and/or nano based materials. Quantify measurement accuracy. (2009, 2011)			
1.6.1	Develop and demonstrate virtual sensors technology	2009	
Virtual sensor technology demonstrated on a ground testbed with 90% accuracy (with respect to ground truth) at the 95% confidence level.			
1.6.2	Develop methods for mining failure precursor signatures.	2010	
At least three novel failure precursor signatures discovered (as confirmed by experts) using historical			

Level 1 Milestones			
Number	**Title**	**Year**	**Dependencies**
Exit Criteria / Metrics			
data contained in the IVHM database.			
1.6.3	Self-healing adaptive network technologies	2010	
Reduce link failure detection time to less than 500ms and reduce overall route convergence time to less than 1 second.			
1.6.4	Wireless communication technology for extreme environments	2011	
Development of integrated transceiver and antenna components, in a package smaller than 1 cubic inch, to operate within constrained space (airfoil), non-high temp environment.			
1.6.5	Integrated analysis and simulation methods with automatic test vector generation	2007	
Demonstrate that integrated analysis and simulation with automatic test matrix generation results in at least 10% more efficient test coverage (in terms of time and number of worst case scenarios identified) for two selected examples as compared to isolated application of analysis, simulation, and test methods.			
1.6.6	Develop multi-objective and multi-disciplinary optimization methods for system analysis and optimization	2010	
In representative design problems, 100% coverage of selected faults achieved (via testability analysis) with 20% fewer design cycles compared to traditional design methods.			
1.6.7	Development and analysis of distributed algorithms for real-time distributed resource management	2008	
Theoretical proof of information integrity and robustness of a candidate distributed algorithm subjected to a minimum of one processing node failure			
1.6.8	IVHM Data interchange standards and protocols	2009	
With NASA participation, an IVHM data interchange standard ratified by a standards body (e.g., RTCA, AIAA, or IEEE).			
1.7.1	Develop compositional verification techniques for complex and modular IVHM models	2010	
In conjunction with the High Confidence Software and Systems (HCSS) coordinating group, develop techniques for improved verification of complex IVHM models and demonstrate compositional verification method on a minimum of two hypothetical designs whose verification would be intractable using existing monolithic approaches.			
1.7.2	Develop analysis capabilities to address multiple failure sources, imperfect models, and imperfect sensors	2009	
Develop new methods and techniques for formal analysis of ultra-reliable distributed protocols and demonstrate that the new capability can accurately identify the classes and combinations of failures under which the architecture provides the correct services. Demonstrate capability on a minimum of two candidate architectures.			

Appendix J: Acronyms

ATA	Air Transport Association
ADAPT	Advanced Diagnostic and Prognostics Testbed
AFRL	Air Force Research Laboratory
AIAA	American Institute of Aeronautics and Astronautics
ALDF	Aircraft Landing Dynamics Facility
ARC	Ames Research Center
ARMD	Aeronautics Research Mission Directorate
AvSP	Aviation Safety Program
BMOD	Bill of Material Object Damage
CAST	Commercial Aviation Safety Team
CS	Civil Service
DARPA	Defense Advanced Research Projects Agency
DFRC	Dryden Flight Research Center
DoD	Department of Defense
DODAF	DoD Architecture Framework
DoE	Department of Energy
DPI	Deputy Project Investigator
DPM	Deputy Program Manager
EAR	Export Administration Regulation
EHWG	Engine and Power Plant Installation Harmonization Working Group
EIDD	Electrical Impedance Damage Detection
EMI	Electromagnetic Interference
EPS	Electrical Power Systems
ESMD	Exploration System Mission Directorate
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Control
FCC	Flight Control Computers
FEAF	Federal Enterprise Architecture Framework
FOD	Foreign Object Damage
FTE	Full Time Equivalent
GPHM	Gas Path Health Management
GRC	Glenn Research Center
HIRF	High-Intensity Radiated Fields
HM	Health Management
HyDE	Hybrid Diagnosis Engine
IEEE	Institute of Electrical and Electronics Engineers
iFEM	Inverse Finite Element Method
IIFD	Integrated Intelligent Flight Deck
ICAO	International Civil Aviation Organization
IRAC	Integrated Resilient Aircraft Control
ITAR	International Traffic in Arms Regulations
ISHM	Integrated Systems Health Management
IVHM	Integrated Vehicle Health Management
JIMDAT	Joint Implementation Measurement Data Analysis Team
JSF	Joint Strike Fighter
LaRC	Langley Research Center

LRU	Line Replaceable Unit
MAPSS	Modular Aero-Propulsion System Simulation
MEMS	Micro-Electromechanical Systems
MOU	Memorandum of Understanding
MSC	Meteorological Services of Canada
NASA	National Aeronautics and Space Administration
NGATS	Next Generation Air Transportation System
NOAA	National Oceanic and Atmospheric Administration
NRA	NASA Research Awards
NRC	National Research Council
NTSB	National Transportation Safety Board
NX	NASA-Xerox
OFRD	Optical Frequency-Domain Reflectometry
OGA	Other Government Agencies
PHM	Prognostics Health Management
PI	Principal Investigator
PIWG	Propulsion Instrumentation Working Group
PM	Project Manager
PRA	Probabilistic Risk Analysis
P-SAR	Propulsion Safety and Affordability Readiness Program
R&D	Research and Development
RF	Radio Frequency
RFI	Request for Information
RFID	Radio Frequency Identification
RTCA	Radio Technical Commission for Aeronautics
SAFETI	Systems and Airframe Failure Emulation Testing and Integration
SC	Special Committee
SEE	Single Event Effects
SBIR	Small Business Innovative Research
SPIDER	Scalable Processor-Independent Design for Enhanced Reliability
UWB	Ultra Wideband
V&V	Verification and Validation
WBS	Work Breakdown Structure
WYE	Work Year Equivalent
X-FEM	Extended Finite Element Model

Appendix K: Bibliography

AIRFRAME HEALTH MANAGEMENT

1. W.H. Prosser, S.G. Allison, S.E. Woodard, R.A. Wincheski, E.G. Cooper, D.C. Price, M. Hedley, M. Prokopenko, D.A. Scott, A. Tessler, J.L. Spangler. Structural Health Management for Future Aerospace Vehicles, The 2nd Australasian Workshop on Structural Health Monitoring (2AWSHM), Melbourne, Australia, December 2004.
2. W. H. Prosser, T. L. Brown, S. E. Woodard, G. A. Fleming, and E. G. Cooper: Sensor Technology for Integrated Vehicle Health Management of Aerospace Vehicles, 2002 Review of Progress in Quantitative NDE Conference, July 14-19 2002, Bellingham, WA
3. Munns, Thomas; Kent, Renee M.; Bartolini, Anthony; "Health Monitoring for Airframe Structural Characterization", NASA CR-2002-211428, February 2002

PROPULSION HEALTH MANAGEMENT

1. Litt, J., Simon, D. L., Meyer, C., DePold, H., Curtiss, J. R., Winston, H., Wang, Y., Statler, I., Gawdiak, Y., "NASA Aviation Safety Program Aircraft Engine Health Management Data Mining Tools Roadmap," NASA TM-2000-210030, ARL-TR-2213, SPIE 4057-37, SPIE 14th Annual International Symposium on Aerospace / Defense Sensing, Simulation and Controls Aerosence, Orlando, FL, April 24-28, 2000.
2. Simon, D.L., "An Overview of the NASA Aviation Safety Program Propulsion Health Monitoring Element," NASA TM-2000-210348, ARL-TR-2272, AIAA-2000-3624, AIAA 36th Joint Propulsion Conference, Huntsville, AL, July 16-19, 2000.
3. Simon, D.L., Garg, S., Hunter, G.W., Guo, T.H., Semega, K.J., "Sensor Needs for Control and Health Management of Intelligent Aircraft Engines," ARL-TR-3251, NASA TM-2004-213202, ASME-GT2004-54324, presented at the ASME Turbo Expo 2004, Vienna, Austria, June 2004.
4. Jonathan S. Litt, Donald L. Simon, Sanjay Garg, Ten-Heui Guo, Carolyn Mercer, Richard Millar, Alireza Behbahani, Anupa Bajwa, and Daniel T. Jensen, "A Survey of Intelligent Control and Health Management Technologies for Aircraft Propulsion Systems," NASA TM-2005-213622
ARL-TR-3413, May 2005.

AIRCRAFT SYSTEMS HEALTH MANAGEMENT

1. Belcastro, C. M., Chowdhury, F., Cheng, Q., Michels, J., Varshney, P., "Distributed Detection With Data Fusion for Aircraft Flight Control Computer Malfunction Monitoring", AIAA Guidance, Navigation, and Control Conference and Exhibit, San Francisco, CA 2005
2. Cheng, Qi; Varshney, Pramod K.; Michels, James, Belcastro, Celeste M.; "Distributed Fault Detection via Particle Filtering and Decision Fusion", Proceedings of Information Fusion 2005, Philadelphia PA, July 2005
3. Chowdhury, Fahmida; Belcastro, Celeste M.; Jiang, Bin; "Fault Detection: The Effect of Unknown Distribution of Residuals". Proceedings of the 23rd Digital Avionics Systems Conference, October 2004
4. Munns, Thomas; Palmer, Matthew; "Health Management Technologies and Experiments for Transport Aircraft Landing Gear", AIAA Guidance, Navigation, and Control Conference and Exhibit, San Francisco, CA 2005
5. Graves, Sharon and Harper, Donald, "Reconfiguration Algorithms for Failure Mitigation Electronics", 2006 MAPLD International Conference, September 26-28, 2006. *(Abstract submitted)*
6. Keymeulen, D., Stoica, A., Zebulum, R., Rajeshuni, R., Katkoori, S., **Graves, S.,** Novak, F., and Antill, C., "Design and Implementation of Self Recovery Electronics System for Extreme Environments", 1rst NASA/ESA Conference on Adaptive Hardware and Systems (AHS-2006), Istanbul, Turkey, June 15-18, 2006. *(submitted)*
7. R. Ingvalson, H. Rotstein, T. Keviczky and G.J. Balas, "Fault detection design for uninhabited aerial vehicles", accepted for publication, *AIAA Journal of Guidance, Dynamics and Control*, December 2005
8. A. Marcos and G.J. Balas, .An Integrated control/diagnosis filter aircraft application", accepted for publication, *International Journal of Robust and Nonlinear Control*, June 2005
9. I. Sz´aszi, A. Marcos, G.J. Balas and J. Bokor, .LPV detection _lter design for a Boeing 747-100/200 aircraft, *AIAA Journal of Guidance, Dynamics and Control*, vol. 28, no. 3, 2005, p. 461-470
10. A. Marcos, S. Ganguli and G.J. Balas, .An Application of *H*¥ fault detection and isolation to a transport aircraft, *IFAC Control Engineering Practice Journal*, vol. 13, no. 1, 2005, p. 105-119
11. J. Bokor and G.J. Balas, .Detection _lter design for LPV systems . A geometric approach,. *Automatica*, vol. 40, pp. 511-518, March 2004

12. A. Marcos and G.J. Balas, .Nested integrated control and diagnostic _lter design,. *IEEE Conference on Decision and Control*, Spain, December 2005
13. A. Macros, G.J. Balas and J. Bokor, .Integrated FDI and control for transport aircraft,. *2005 AIAA Guidance Navigation and Control Conference,* San Francisco, CA, August 2005
14. R. Ingvalson, H. Rotstein, T. Keviczky and G.J. Balas, .Fault detection design for uninhabited aerial vehicles, *2005 AIAA Guidance, Navigation and Control Conference,* San Francisco, CA, August 2005
15. H. Rotstein, R. Ingvalson, T. Keviczky and G.J. Balas, .Input-dependent threshold function for an actuator fault detection _lter,. *16*th *International Federation of Automatic Control (IFAC) World Congress*, Prague CZ, July 2005
16. A. Marcos, S. Ganguli and G.J. Balas, .New strategies for fault tolerant control and fault diagnostic,. *IFAC SAFEPROCESS Conference*,Washington D.C. November 2003
17. J. Bokor, Z. Szabo and G.J. Balas, .Inversion of LPV systems and its application to fault detection,. *IFAC SAFEPROCESS Conference*,Washington D.C. November 2003
18. A. Marcos, S. Ganguli and G.J. Balas, .Application of H¥ fault detection and isolation to a Boeing 747-100/200 longitudinal motion,. *AIAA Guidance, Navigation and Control Conference,* August 2002, AIAA-2002-4944
19. I. Szaszi, A. Marcos, G.J. Balas and J. Bokor, .LPV detection _lter design for Boeing 747-100/200,. *American Control Conference*, Anchorage, AK, May 2002, pp. 4232-7
20. A. Marcos, S. Ganguli and G.J. Balas, .An LPV fault detection and isolation application to the longitudinal motion of a Boeing 747-100/200,. *AIAA Guidance, Navigation and Control Conference*, August 2002
21. G.J. Balas, J. Bokor and Z. Szabo, .Failure detection for LPV systems: a geometric approach,. *American Control Conference*, June 2002, pp. 4421-6
22. S. Ganguli, A. Marcos, I. Szaszi, G.J. Balas and J. Bokor, .Application of FDI to a Nonlinear Boeing-747 Aircraft,. *Mediterranean Control and Automation Conference*, July 2002
23. I. Szaszi, G.J. Balas and J. Bokor, .Design of FDI _lter for an aircraft control system,. *2002 American Control Conference*, Anchorage, AK, May 2002, pp. 4232-7
24. J. Bokor and G.J. Balas, .Detection _lter design within the LPV framework,. *Proceeding of 19th Digital Avionics Systems Conference*, Philadelphia, PA, October 2000, GA3/1-5, Volume 2

ENVIRONMENTAL HAZARDS

Ionizing Radiation

1. Eure, Kenneth; Belcastro, Celeste M.; Koppen, Daniel; Hess, Richard; Stange, Kent; Vahala, Linda; Ferguson, Matthew; ; "Closed-Loop Neutron Particle Effects Testing on a Recoverable Flight Control Computer". Proceedings of the 23rd Digital Avionics Systems Conference, October 2004
2. Eure, Kenneth, Belcastro, Celeste M., Gray, W. Steven, Gonzalez, Oscar: Neutron Particle Effects on a Quad-Redundant Flight Control Computer, Digital Avioincs Systems Conference, October 2003
3. Hess, Richard; Stange, Kent; et. al.; "Summarization of Neutron Test Results on a Recoverable Computer System", AIAA Guidance, Navigation, and Control Conference and Exhibit, San Francisco, CA 2005
4. J. W. Wilson et al., "Atmospheric Ionizing Radiation (AIR) Analysis, Results and Lessons Learned From the June 1997 Er-2 Campaign" NASA CP-2003-212155
5. J. W. Wilson et al., Transport Methods and Interactions for Space Radiations NASA RP-1991-1257
6. J. L. Shinn et al., "Effects of Target Fragmentation on Evaluation of LET Spectra from Space Radiation on Low-Earth Orbit (LEO) Environment: Impact on SEU Predictions" 32nd Annual International Nuclear and Space Radiation Effects Conference 1995
7. D. Binder, E.C. Smith, and A.B. Holman, "Satellite Anomalies from Galactic Cosmic Rays," IEEE Transactions on Nuclear Science, Vol. NS-22, 2675 (1075)
8. Normand, E., and T.J. Baker, 1993, 'Altitude and Latitude Variations in Avionics SEU and Atmospheric Neutron Flux', IEEE Trans. Nuclear Science, vol. 40 n0. 6, pp. 1484-1490
9. J. F. Ziegler and W. A. Lanford, "Effect of Cosmic Rays on Computer Memories," Science, Vol. 206, pp. 776, 1979.
10. A. Taber and E. Normand, "Investigation and Characterization of SEU Effects and Hardening Strategies in Avionics," IBM Report 92-L75-020-2, Aug. 1992, republished as DNA-Report DNA-TR-94-123, Defense Nuclear Agency, Feb. 1995.
11. R. Chambers, "Single Event Upset (SEU) phenomenon caused by low level / ground level radiation," NAVAIR White Paper, January 17, 2000

Electromagnetic Interference

1. Ely, Jay; "Electromagnetic Interference to Flight Navigation and Communication Systems: New Strategies in the Age of Wireless", AIAA Guidance, Navigation, and Control Conference and Exhibit, San Francisco, CA 2005
2. Nguyen, Truong X., "Evaluation of a Mobile Phone for Aircraft GPS Interference", NASA/TP-2004-213395, October 2004.

3. Nguyen, Truong X.; Koppen, Sandra V.; Smith, Laura J.; Williams, Reuben A.; Salud, Maria Theresa P., “Third Generation Wireless Phone Threat Assessment for Aircraft Communication and Navigation Radios”, NASA/TP-2005-213537, March 2005.
4. Nguyen, Truong X., “Cumulative Interference to Aircraft Radios From Multiple Portable Electronic Devices”, November 2003.
5. Ely, Jay J.; Nguyen, Truong X.; Koppen, Sandra V.; Beggs, John H.; Salud, Maria Theresa P., “Wireless Phone Threat Assessment and New Wireless Technology Concerns for Aircraft Navigation Radios”, NASA/TP-2003-212446, July 2003.
6. Nguyen, Truong X.; Koppen, Sandra V.; Ely, Jay J.; Williams, Reuben A.; Smith, Laura J.; Salud, Maria Theresa P.,“Portable Wireless LAN Device and Two-Way Radio Threat Assessment of Aircraft VHF Communication Radio Band”, NASA/TP-2003-212438, July 2003.
7. Nguyen, Truong X.; Ely, Jay J., “Determination of Receiver Susceptibility to Radio Frequency Interference From Portable Electronic Devices; 21st Digital Avionics Systems Conference”, 21st Digital Avionics Systems Conference, October 2002.
8. Nguyen, Truong X.; Ely, Jay J.; Koppen, Sandra V., “Mode-Stirred Method Implementation for HIRF Susceptibility Testing and Results Comparison with Anechoic Method”, NASA/TM-2001-211033, April 2001.
9. Ely, Jay J.; Nguyen, Truong X.; Dudley, Kenneth L.; Scearce, Stephen A.; Beck, Fred B.; Deshpande, Manohar D.; Cockrell, C. R., “Investigation of Electromagnetic Field Threat to Fuel Tank Wiring of a Transport Aircraft”, NASA/TP-2000-209867, March 2000.
10. Nguyen, Truong X.; Dudley, Kenneth L.; Scearce, Stephen A.; Ely, Jay J.; Richardson, Robert E.; Hatfield, Michael O., “RF Coupling Into the Fuel Tank of a Large Transport Aircraft From Intentionally Transmitting Peds in the Passenger Cabin; 19th Digital Avionics Systems Conference”, December 1999.
11. Ely, Jay J.; Nguyen, Truong X.; Scearce, Stephen A., “The Influence of Modulated Signal Risetime in Flight Electronics Radiated Immunity Testing With a Mode-Stirred Chamber”, NASA/TM-2000-209844, January 2000
12. Ely, Jay J.; Nguyen, Truong X.; Koppen, Sandra V.; Beggs, John H.; Salud, Maria Theresa P.,” Wireless Phone Threat Assessment and New Wireless Technology Concerns for Aircraft Navigation Radios”, NASA/TP-2003-212446, July 2003.
13. Nguyen, Truong X.; Koppen, Sandra V.; Ely, Jay J.; Williams, Reuben A.; Smith, Laura J.; Salud, Maria Theresa P., “Portable Wireless LAN Device and Two-Way Radio Threat Assessment for Aircraft VHF Communication Radio Band”, NASA/TP-2003-212438, July 2003.
14. Ely, Jay J.; Nguyen, Truong X.; Koppen, Sandra V.; Salud, Maria Theresa P., “Electromagnetic Interference Assessment of CDMA and GSM Wireless Phones to Aircraft Navigation Radios”, 21st Digital Avionics Systems Conference, 2002.
15. Salud, Maria Theresa P., “Portable Integrated Wireless Device Threat Assessment to Aircraft Radio System”, NASA/CR-2004-21351, March 2004.
16. Salud, Maria Theresa P., “Investigation of RF Emissions From Wireless Networks as a Threat to Avionic Systems”, NASA/CR-2002-211941, October 2002.
17. Koppen, Sandra V., “A Description of the Software Element of the NASA EME Flight Tests”, NASA-CR-201635,
18. Koppen, Sandra V., “A Description of the Software Element of the NASA Portable Electronic Device Radiated Emissions Investigation”, NASA/CR-2002-211675, May 2002.
19. M. D. Deshpande, C. J. Reddy, P. I. Tiemsin, and R. Cravey, "A New Approach to Estimate Complex Permittivity of Dielectric Materials at Microwave Frequencies Using Waveguide Measurements", IEEE Transactions on Microwave Theory and Techniques, Volume 45, Number 3, March 1997.
20. S. M. Rao, C. C. Cha**,** R. L. Cravey**,** and D. L. Wilkes, "Arbitrarily Shaped Conducting Bodies Coated with Lossy Materials of Arbitrary Thickness", IEEE Transactions on Antennas and Propagation, May 1991.
21. Robin W. Cravey, Robert Sternlicht, and Charles E. Ryan, Jr., "Finite Element Analysis of Over-Moded Waveguides Using Silvester's Algorithm", Microwave Theory and Techniques, February 1987.
22. R. L. Cravey**,** M. D. Deshpande, C. J. Reddy, P. I. Tiemsin, "Evaluation of Complex Permittivities of Multilayer Dielectric Substrates at Microwave Frequencies Using Waveguide Measurements", 1996 Antenna Measurement Techniques Association Symposium, October 1996, Seattle, WA.
23. M. D. Deshpande, C. J. Reddy, P. I. Tiemsin, R. Cravey, "A New Approach to Estimate Complex Permittivity of Dielectric Materials at Microwave Frequencies Using Waveguide Measurements", 1995 Antenna Measurement Techniques Association Symposium, November 1995.
24. Robin L. Cravey and Chung Chi Cha, "Asymptotic Evaluation of the Physical Optics Integral for Generalized Ellipsoidal Frusta", Applied Computational Electromagnetics Conference, March 21-23, 1989.
25. L. C. Schroeder, R. L. Cravey, M. J. Scherner, C. P. Hearn, and H.-J. C. Blume, "Emissivity Measurements in Thin Metallized Membrane Reflectors Used for Microwave Radiometer Sensors", NASA Technical Memorandum #110179, June 1995.
26. Robin L. Cravey, "Finite Difference Time Domain Grid Generation from AMC Helicopter Models", NASA Technical Memorandum #107679, September 1992.

IVHM ARCHITECTURES AND DATABASES

1. Munns, Thomas; “Integrated Health Management and Structural Characterization, Refinement, Test, and Evaluation”, Final Technical Report, NASA Contract GS-23G-0201K, BPA L-71360D, Order #6, January 2006
2. Bartolini, Anthony; Firestone, Todd M.; Kent, Renee M.; “Aircraft Condition Analysis and Management System for Transports”, AIAA Guidance, Navigation, and Control Conference and Exhibit, San Francisco, CA 2005
3. Mukkamala, R., Agarwal, N., Kumar, P., Sundaram, P., “Designing Domain-Specific HUMS Architectures: An Automated Approach”, Proceedings of the IEEE/AIAA 22th Digital Avionics Systems Conference; 12-16 October 2003, Indianapolis, IN, pp. 11.D.2-1 – 11.D.2-13
4. Mukkamala, R., “Distributed Scalable Architectures For Health Monitoring Of Aerospace Structures”, Proceedings of the IEEE/AIAA 19th Digital Avionics Systems Conference; 7-13 October 2000, Philadelphia, PA, pp. 6.C.4.1 – 6.C.4.8
5. Mukkamala, R., Bhoopalam, K., Dammalpati, S., “Design and Analysis of a Scalable Kernel for Health Management of Aerospace Structures”, Proceedings of the IEEE/AIAA 20th Digital Avionics Systems Conference; 14-18 October 2001, Daytona Beach, FL, pp. 3.D.2.1 – 3.D.2.10
6. Mukkamala, R., Adavi, V., Agarwal, N., Gullapalli, S., Kumar, P., Sundaram, P., “HADL: HUMS Architectural Description Language”, Proceedings of the IEEE/AIAA 22th Digital Avionics Systems Conference; 12-16 October 2003, Indianapolis, IN, pp. 11.D.3-1– 11.D.3-10
7. Mahyar R. Malekpour, Radu Siminiceanu; “Comments on the Byzantine Self-Stabilizing Pulse Synchronization Protocol: Counterexamples.” NASA Technical Memorandum NASA/TM-2006-213951, February 2006.
8. Paul Miner, Alfons Geser, Lee Pike, and Jeffery Maddalon. A unified fault-tolerance protocol. In *Yassine Lakhnech and Sergio Yovine, editors, Formal Techniques, Modeling and Analysis of Timed and Fault-Tolerant Systems (FORMATS-FTRTFT)*, volume 3253 of Lecture Notes in Computer Science, pages 167--182. Springer, 2004
9. *Alfons Geser and Paul Miner.* A New On-line Diagnosis Protocol for the SPIDER Family of Byzantine Fault Tolerant Architectures. NASA TM, 2003
10. Malekpour, Mahyar R.; “A Self-Stabilization Protocol for Distributed Clock Synchronization Systems”, NASA/TM-2006, under review
11. O. R. González, W. S. Gray, and A. Tejada, “Analytical Tools for the Design and Verification of Safety Critical Control Systems,” *SAE Transactions, Journal of Aerospace*, Section 1, Vol. 110, pp. 481-490, 2002
12. O. R. González, A. Tejada , and W. S. Gray, “Analysis of Design Trade-Offs in the Rollback Recovery for Fault Tolerant Digital Control Systems,” Proceedings of the 2002 American Control Conference, Anchorage, Alaska, pp. 4801-4806, 2002
13. A. F. Mehr and I. Y. Tumer, "Risk based decision making for managing resources during the design of complex aerospace systems." *ASME Journal of Mechanical Design*. Special issue on Risk Based Design. In print. February 2006.
14. I. Y. Tumer, R. B. Stone, "Mapping Function to Failure during High-Risk Component Development." Journal of *Research in Engineering Design*. Vol. 14, 2003, pp.25-33.
15. R. B. Stone, I. Y. Tumer, M. VanWie, "The Function-Failure Design Method." ASME *Journal of Mechanical Design*. 127(3): 397-407. 2005.
16. R. B. Stone, I. Y. Tumer, M. E. Stock, "Linking product functionality to historical failures to improve failure analysis in design." Journal of *Research in Engineering Design*. In print. 2005.
17. S. G. Arunajadai, R. B. Stone, I. Y. Tumer, "Failure mode identification through clustering analysis." *Quality and Reliability Engineering International Journal*. 20:511-526. 2004.
18. I. Y. Tumer, "Towards ISHM Co-Design: Methods and practices for fault avoidance and management during early phase design". *1st Integrated Systems Health Engineering and Management Forum* (to be published as a book chapter). November 2005, Napa, CA.
19. K. Grantham, M. VanWie, R. Stone, I. Y. Tumer, and F. Barrientos, "An Analysis of Risk and Function Information in Early Stage Design." In ASME *Design Theory and Methodology Conference*. DETC2005-85405. Long Beach, CA, 2005.
20. A. F. Mehr, I. Y. Tumer, E. Barszcz, "Optimal Design of Integrated Systems Health Management (ISHM) Systems for Improving the Safety of NASA's Exploration Missions: A Multidisciplinary Design Approach", *WCSMO'06*, Brazil, 2005.
21. K. Grantham, R. Stone, and I. Y. Tumer, "Function-Based Risk Assessment: Mapping Function to Likelihood." In ASME *Design Theory and Methodology Conference*. DETC2005-85053. Long Beach, CA, 2005.
22. R. Hutcheson and I. Y. Tumer, "Function-based design of a spacecraft power subsystem diagnostics testbed". ASME *International Mechanical Engineering Congress and Exposition*. IMECE2005-81120. Orlando, FL. 2005.
23. R. Hutcheson and I. Y. Tumer, "Function-based Co-design Paradigm for Robust Health Management." *The 5th International Workshop on Structural Health Monitoring*. Stanford, CA. September 2005.

24. I. Y. Tumer, A. F. Mehr, F. A. Barrientos, D. Ullman, "An Information-Exchange Tool for Capturing and Communicating Decisions during Early-Phase Design and Concept Evaluation." ASME *International Mechanical Engineering Congress and Exposition*. IMECE2005-81690. Orlando, FL. 2005.
25. S. J. Uder, R. B. Stone, and I. Y. Tumer, "Failure analysis in subsystem design for space missions." ASME *Design Theory and Methodology Conference*. DETC2004-57338. Salt Lake City, UT 2004.

VERIFICATION AND VALIDATION

1. Bateman, A., C. Elks, D. Ward and J. Schierman, Barron Associates Inc., “New Verification and Validation Methods for Guidance/Control of Advanced Autonomous Systems” Infotech@Aerospace, Arlington, Virginia, Sep. 26-29, 2005
2. Jacklin, Stephen A. et al: "Verification, Validation, and Certification Challenges for Adaptive Flight-Critical Control System Software". Proceedings of the AIAA Guidance, Navigation, and Control Conference, August, 2004. (Invited Session on Validation of Advanced Flight Control Systems)
3. Belcastro, Christine M., Belcastro, Celeste M.: On the Validation of Safety Critical Aircraft Systems, Part I: An Overview of Analytical and Simulation Methods, Invited Session, AIAA Guidance Navigation and Control Conference, August 2002, Austin TX
4. Belcastro, Celeste M., Belcastro, Christine M.: On the Validation of Safety Critical Aircraft Systems, Part II: An Overview of Experimental Methods, Invited Session, AIAA Guidance Navigation and Control Conference, August 2002, Austin TX
5. Paul S. Miner, Victor A. Carreño, Mahyar Malekpour, and Wilfredo Torres; “A Case-Study Application of RTCA DO-254: Design Assurance Guidance for Airborne Electronic Hardware”, 19th Digital Avionics Systems Conference, October 2000

SYSTEM INTEGRATION AND ASSESSMENT

1. Fighter/Attack Collision Avoidance Systems Business Case, Defense Oversight Council Aviation Safety Improvements Task Force Safety Technology Working Group, January 2006
2. Murphy, D.A., T.E. Munns, and R.M. Kent. 2000. Operational and Cost Benefit Considerations Associated with Sensor-Based Structural Health Monitoring. Pp. 6.C.3-1-6.C.3-7 in 19th Digital Avionics System Conference Proceedings. Madison, Wisconsin: Omnipress.
3. Munns, Thomas; Beard, Richard; Culp, Aubrey; Murphy, Dennis; Kent, Renee; “Analysis of Regulatory Guidance for Health Monitoring”; NASA CR-2000-210643, December 2000
4. Kent, Renee; Murphy, Dennis; “Health Monitoring System Technology Assessments – Cost Benefit Analysis”, NASA CR-2000-209848, January 2000